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Final Report

ORIGINAL CONTAINS
COLOR ILLUSTRATIONS
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Part A: Cirrus Ice Crystal Nucleation and Growth
Part B: Automated Analysis of Aircraft Ice Particle Data

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(NASA-CR-199371) PART A: CIRRUS
ICE CRYSTAL NUCLEATION AND GROWTH.
PART B: AUTOMATED ANALYSIS OF
AIRCRAFT ICE PARTICLE DATA Final
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ABSTRACT

Specific measurements of cirrus crystals by aircraft and temperature modified CN are used to specify measurements necessary to provide a basis for a conceptual model of cirrus particle formation. Key to this is the ability to measure the complete spectrum of particles at cirrus levels. The most difficult regions for such measurement is from a few to 100 μm , and uses a replicator. The detail of the system to automate replicator data analysis is given, together with an example case study of the system provided from a cirrus cloud in FIRE II, with particles detectable by replicator and FSSP, but not 2DC.

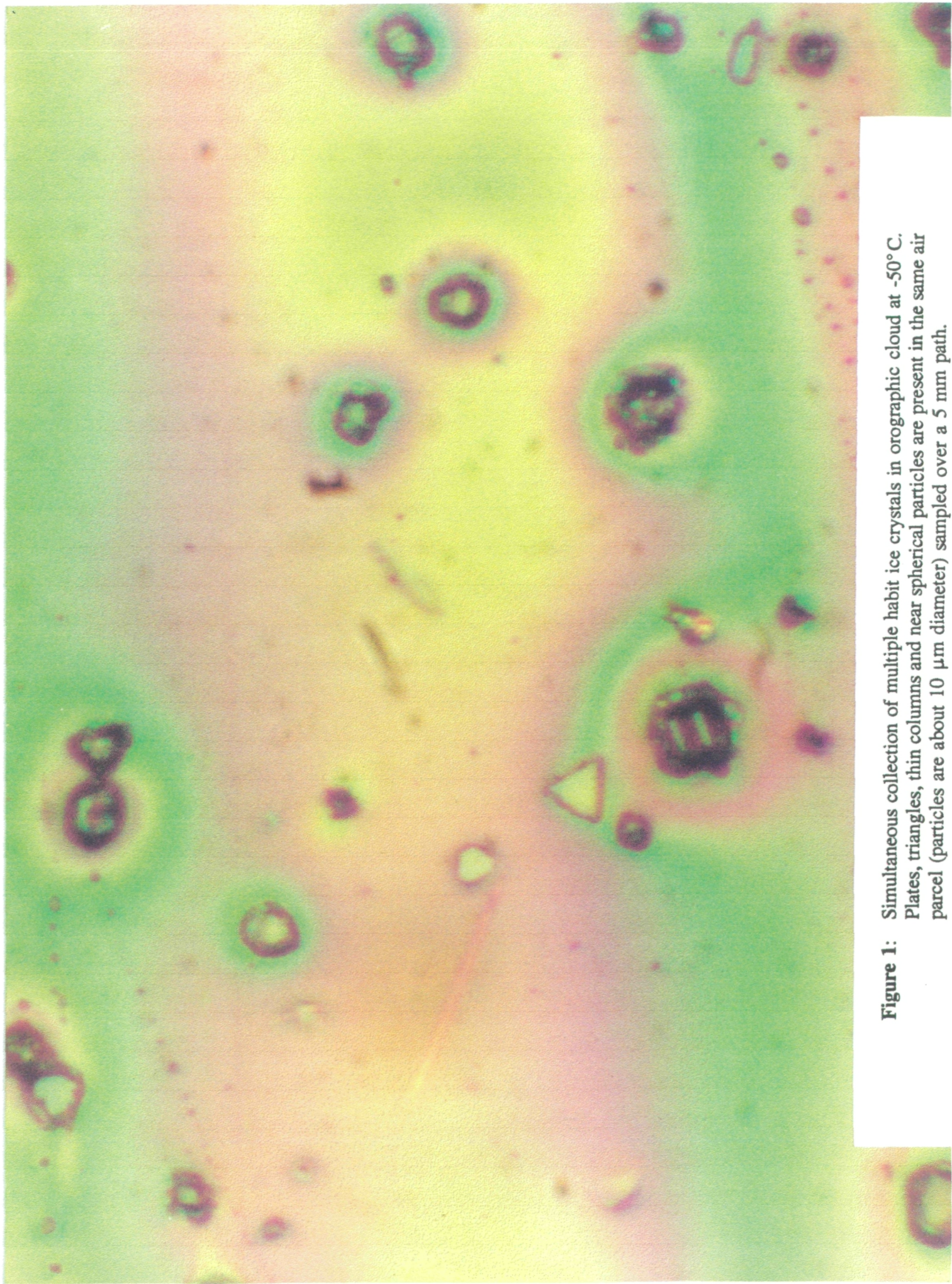


Figure 1: Simultaneous collection of multiple habit ice crystals in orographic cloud at -50°C . Plates, triangles, thin columns and near spherical particles are present in the same air parcel (particles are about $10\text{ }\mu\text{m}$ diameter) sampled over a 5 mm path.

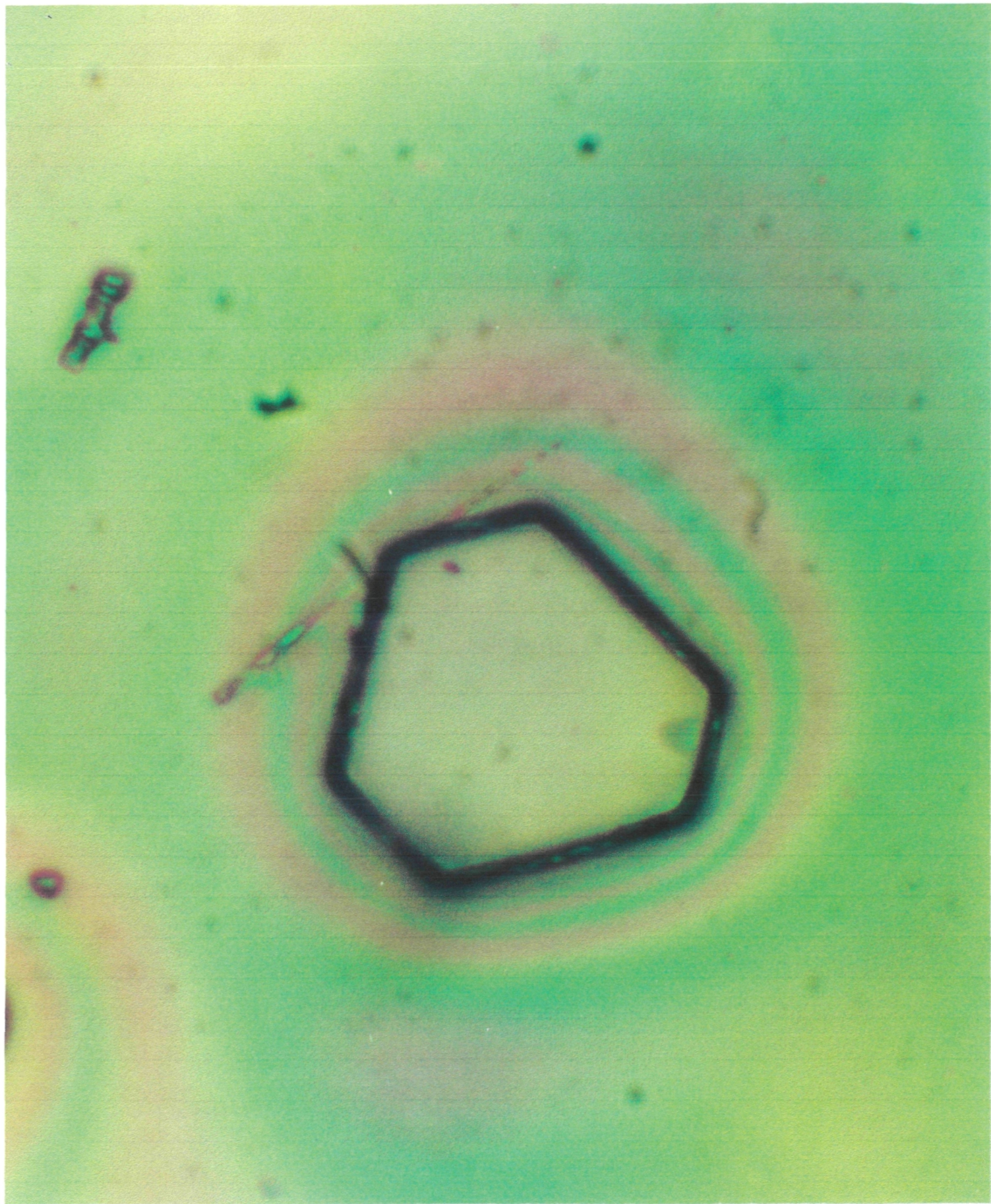


Figure 2: A thin plate showing 3 fold symmetry about 100 μm diameter.

Part A: CIRRUS ICE CRYSTAL NUCLEATION AND GROWTH

1. Introduction

Techniques and protocols are developed for measurements by aircraft of the size, shape, density (mass) spectra of ice crystals which occur in cirrus clouds within the temperature range approximately -30 to -60°C. The ultimate purpose of the study is to relate *in situ* measurements to radiation transfer at a variety of wavelengths both in the solar and thermal infrared spectrum. In particular, the aim is to derive criteria for the formation and size spectrum of cirrus over a depth where ice supersaturation is reached. This will use results from a large scale model and a measured or inferred spectrum of vertical velocities and measured CCN spectra to predict the ice nucleation, growth and ultimately the cirrus optical properties.

2. Data and Instrumentation

Data for test analysis have come from several projects. In particular:

- FIRE II (Kansas 1991) - University of North Dakota (UND) Citation, collaboration with M. Poellott.
- TOGA-COARE (1993, E. Pacific Ocean) - DC-8, collaboration with R. Pueschel.
- EUCREX (1993, N. Scotland) - Falcon, collaboration with P. Wendling
- ARM (1994 Oklahoma) - UND Citation, collaboration with K. Sassen/M. Poellott

Key instrumentation is a formvar replicator designed and constructed at DRI, with a sampling rate of about 1.0 l s^{-1} , and a spatial resolution of 1 - 2 m. The instrument is capable of sampling particles down to a few μm and up to 1 to 2 mm simultaneously. Analysis is by microscopy (Figs. 1 and 2), a stop frame projector and a new automated analysis system (Part B). This uses pattern recognition technology automated for uniform well defined particles and a mouse for individual complex particles when there is a wide spread of particle shapes or there is data of poor quality. Whilst formvar analysis is still labor intensive it has demonstrated conclusively some important aspects of the structure of cirrus clouds (see next section). It serves to locate regions where PMS sampling may be unreliable and where problems may arise. For example,

the FSSP probe is typically unreliable (over-counts) in the presence of a few large ice crystals (Gardiner and Hallett, 1985). Size problems occur for non spherical particles and also with particles where refractive index differs from 1.0 in an arbitrary way - as ice with air bubbles entrapped, or with some content of H_2SO_4 . Uncertainties exist with 2DC data, which records only particles down to about 100 μm . Thus, sometimes area estimation is seriously in error when smaller particles are present in large numbers (Arnott et al, 1994). Combination of the data from these different instruments to produce spectra of a variety of properties is a tedious, time consuming but a necessary part of the analysis. Development of this methodology has been undertaken in this work. A new instrument (the cloudscope, Arnott et al, 1995) using different technology is also becoming available, and use of data collected in ARM is being made to determine its utility and the techniques which can be used for automating data analysis.

3. Nucleation of Cirrus Particles

Nuclei are necessary for initiation of cirrus particles, and a simple physical argument demonstrates that the most likely route is for hygroscopic nuclei to grow and dilute with increasing supersaturation, and to freeze. The freezing process may be by homogeneous nucleation at temperatures below $-38^\circ C$ and heterogeneous nucleation above this temperature. Heterogeneous nucleation requires the presence of insoluble mineral particles, whose lattice structure has some similarity to the ice lattice. A direct approach to this problem is to measure CCN spectra at this level. This is being done, and instrumentation (Hudson 1989, CCN Spectrometer) is being made ready for use in SUCCESS. We have made extensive analysis of temperature qualified CN (concentration measured by a TSI 3010) in TOGA COARE. A furnace characterizes particles as sulfuric acid (disappear above $120^\circ C$), ammonium sulfate about $200^\circ C$ sodium chloride at $600^\circ C$ and insoluble above $700^\circ C$. The latter particles are potential ice nuclei; the former potential CCN. The number measured in both cases will give an upper limit.

The results show that at high levels (40,000 ft $-50^\circ C$) over the Pacific, clean air CN concentration is about 100 cm^{-3} . However, significant regions exist over the E. Pacific where concentrations reach higher than $5,000\text{ cm}^{-3}$ at this level (Figs. 3-11). In particular, there is evidence that on occasion substantial concentrations of sulfuric acid particles exist, and also

ammonium bisulfate/sulfate particles. The refractory particle content is low, sometimes (but not always) in the noise, of a few cm^{-3} , although occasionally as large as 10 cm^{-3} . Analysis is underway of several case studies to provide a more substantial basis for these situations.

4. The model

The data can be synthesized to produce a simple model of cirrus particle formation, as indicated in section 1 (Fig. 12). The basic physics of the model releases water vapor as an air parcel rises at a prescribed rate; the vapor is redescended to CCN as they are activated and grow as cloud droplets, leading to an ambient supersaturation. As the temperature falls, diluted droplets freeze heterogeneously (according to an empirical scheme related to the concentration of refractory particles) and in the absence of such particles by homogeneous nucleation. It is concluded from the analyses that in order to implement this model, much better insight is required in terms of the vertical velocity probability during cirrus clouds formation particularly at temperatures near -40°C , where droplet dilution, nucleation, and ice vapor growth occur (Fig. 13). It is pointed out that this is only possible from the ground using Doppler Lidar (accuracy 10's cm s^{-1}) and only in extended anvil cirrus where no intervening lower cloud exists; it is possible from satellite Doppler Lidar, but the limited accuracy here (few m s^{-1}) is only useful for deep convective tops. Aircraft measurements of vertical velocity on cirrus scale ($\text{few } 100 \text{ m}$) are not adequate for these small velocities in cirrus, satellite measurement cannot resolve sufficiently small regions (Baker et al, 1995).

5. Conclusions

These considerations lead to the following desiderata:

- CCN measurements at cirrus levels and their relation to cirrus crystal concentration and habit.
- Vertical velocity at cirrus levels over a few 10's m scale

The former has instrumentation available and plans are underway for its use in SUCCESS and elsewhere; the latter is possible through ground or aircraft Doppler Lidar, only. Both of these topics need to be pursued with some vigor in order to give a better insight into the cirrus problem and the construction of a usable conceptual model.

6. References:

- Arnott, W. P., Y.Y. Dong, J. Hallett and Michael R. Poellot, 1994: Observations and importance of small ice crystals in a cirrus cloud from FIRE II data, 22 Nov 1994. *J. Geophys. Res.*, **99**, 1371-1381.
- Arnott, W.P., Y. Dong, R. Purcell and J. Hallett, 1995: Direct Airborne Sampling of Small Ice Crystals and the Concentration and Phase of Haze Particles. Ninth Symposium on Meteorological Observations and Instrumentation, Charlotte, North Carolina, 27-31 March 1995.
- Baker, W.E., G.D. Emmitt, F. Robertson, R.M. Atlas, J.E. Molinari, D.A. Bowdle, J. Paegle, R.M. Hardesty, R.T. Menzies, T.N. Krishnamurti, R.A. Brown, M.J. Post, J.R. Anderson, A.C. Lorenc, and J. McElroy, 1995: Lidar-Measured Winds from Space: A Key Component for Weather and Climate Prediction. *Bulletin*, American Meteorological Society, 869-888.
- Foster, T., W.P. Arnott, J. Hallett and R. Pueschel, 1995: Measurements of ice particles in tropical cirrus anvils: Importance in radiation balance. AMS Conference on Cloud Physics, January 15-20, 1995, Dallas, Texas.
- Foster, T.C. and J. Hallett, 1993: Ice crystals produced by expansion: Experiments and applications to aircraft-produced ice. *J. Applied Meteor.*, **32**, 716-728.
- Gardiner, B.A. and J. Hallett, 1985: Degradation of in-cloud forward scattering spectrometer probe measurements in the presence of ice particles. *J. Oceanic & Atmos. Tech.*, **2**, 171-180.
- Hudson, J.G., 1989: An instantaneous CCN spectrometer. *Tech. J. Atmos. & Ocean. Techn.*, **6**, 1055-1065.
- A presentation of this work has been made at the IUGG 1995 in Boulder, Colorado by J. Hallett, J.G. Hudson and R. Pueschell: Aerosol in Tropical Cirrus.
Two papers are in preparation for formal publication.

Flight 105 CN Data

January 5-6, 1993

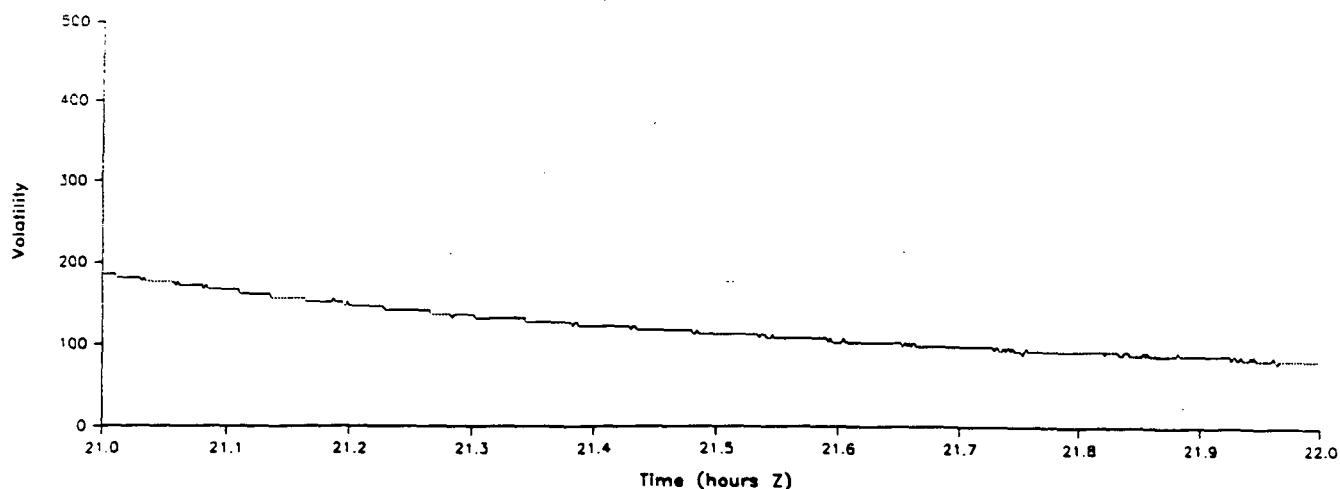
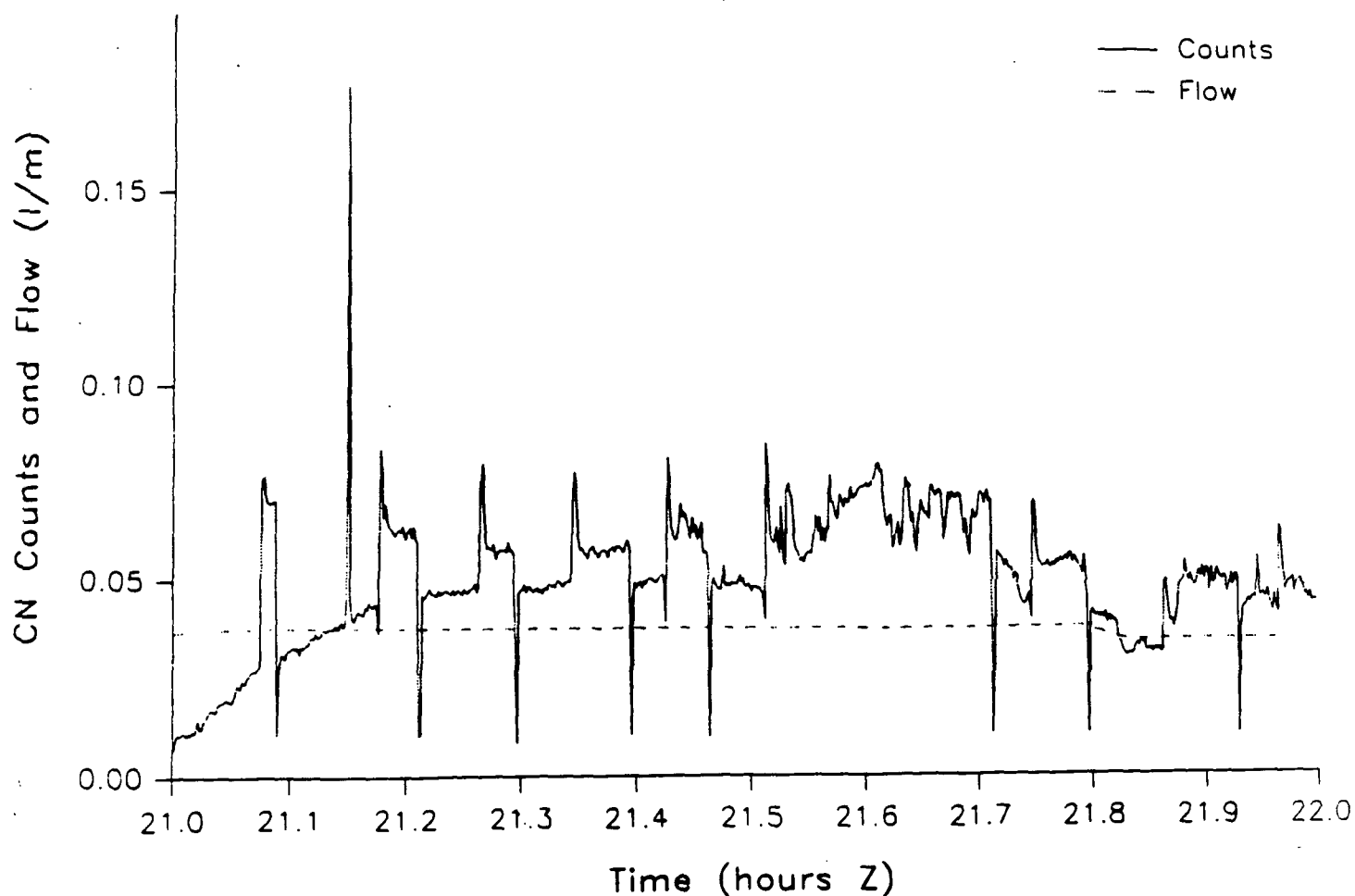
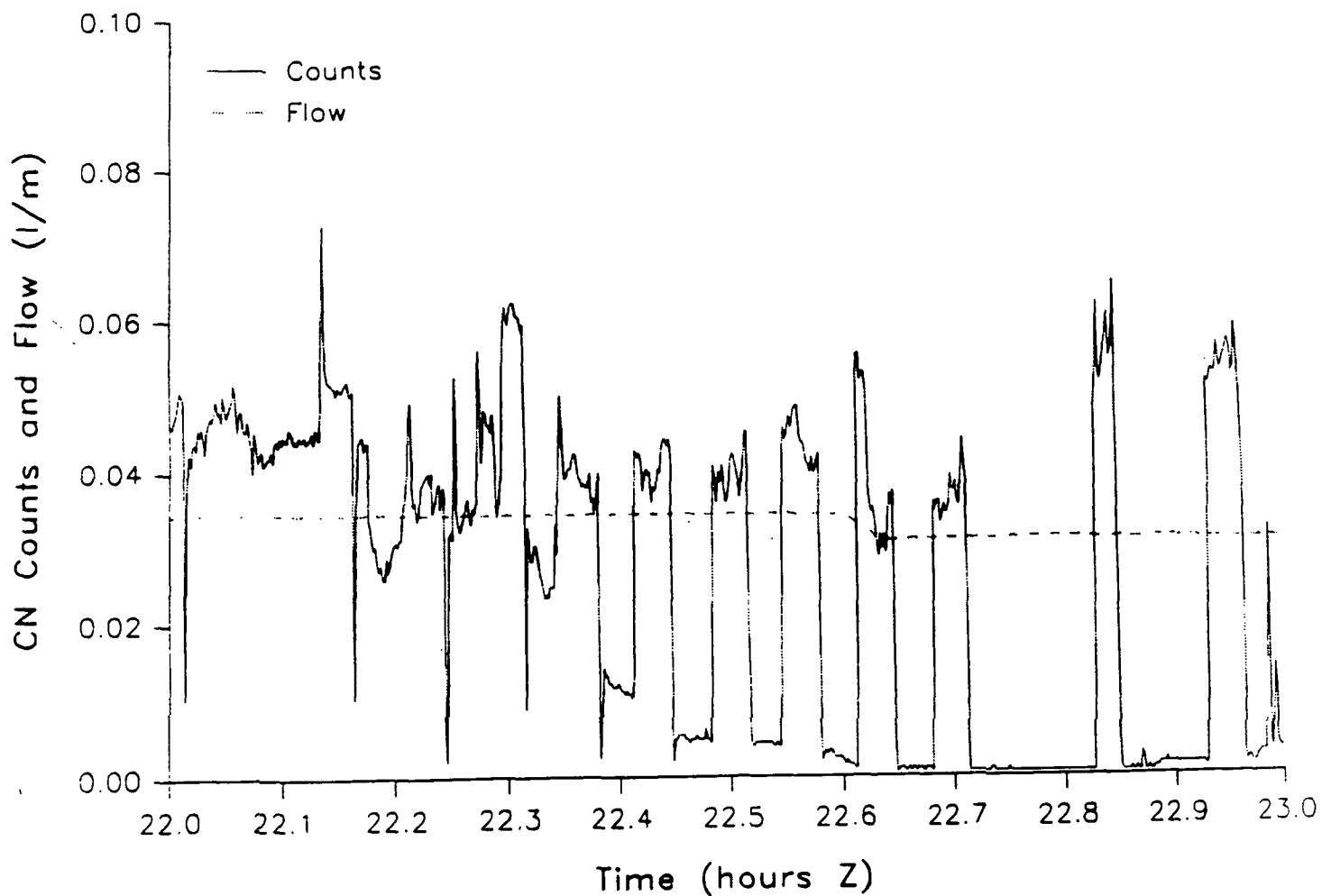
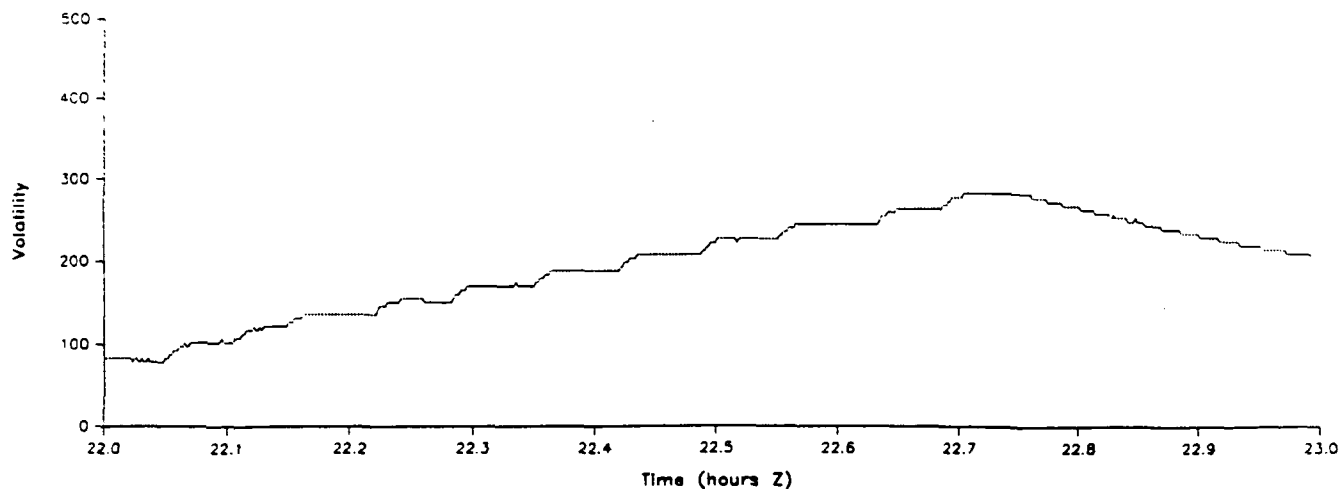


Figure 3: Temperature qualified CN counts at 40,000 ft over the S. Pacific. The sampling is multiplexed between heated and unheated sample at 10-15 minute intervals. Absolute concentration about 200 cm^{-3} . Note that most particles have disappeared by 270°C at 22.7 hours, the range of temperature for greatest reduction rate is about 150°C .



Flight 105 CN Data

January 5-6, 1993



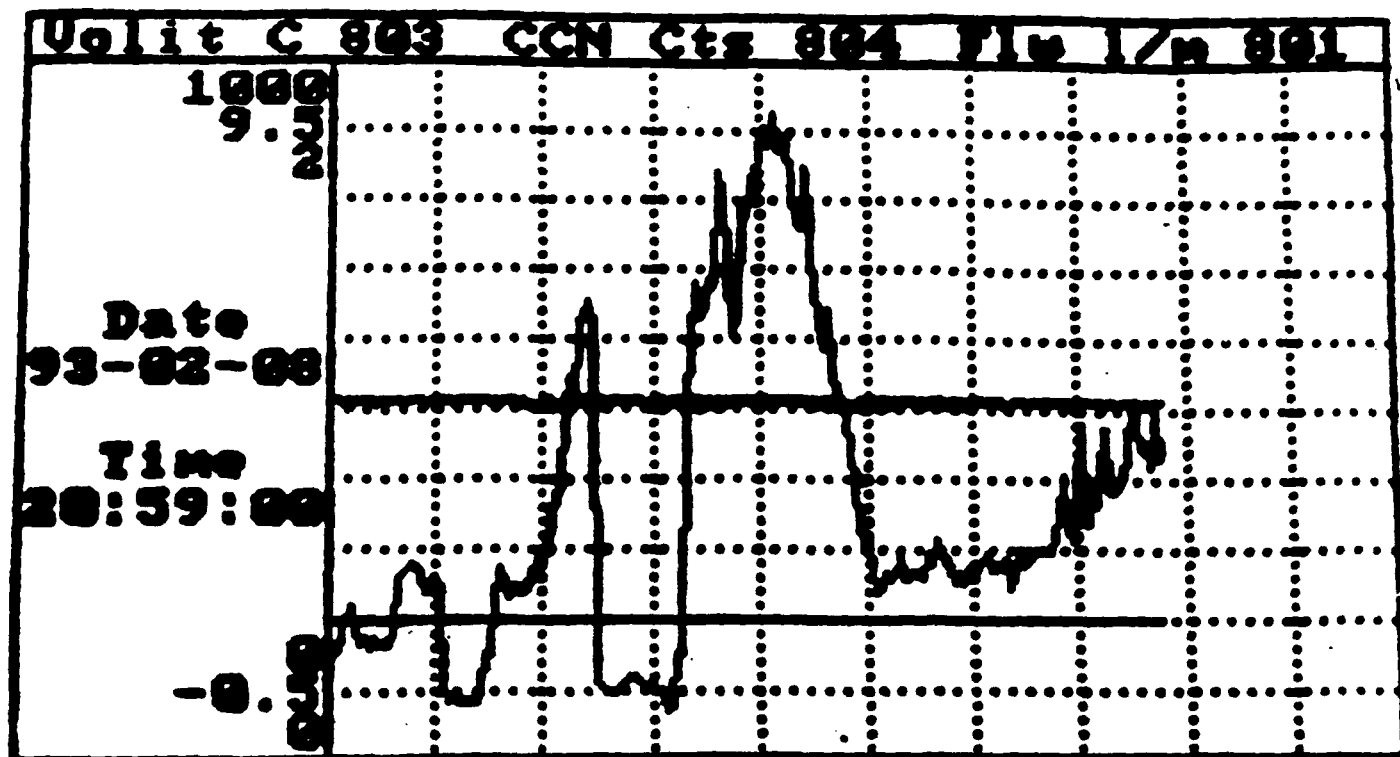
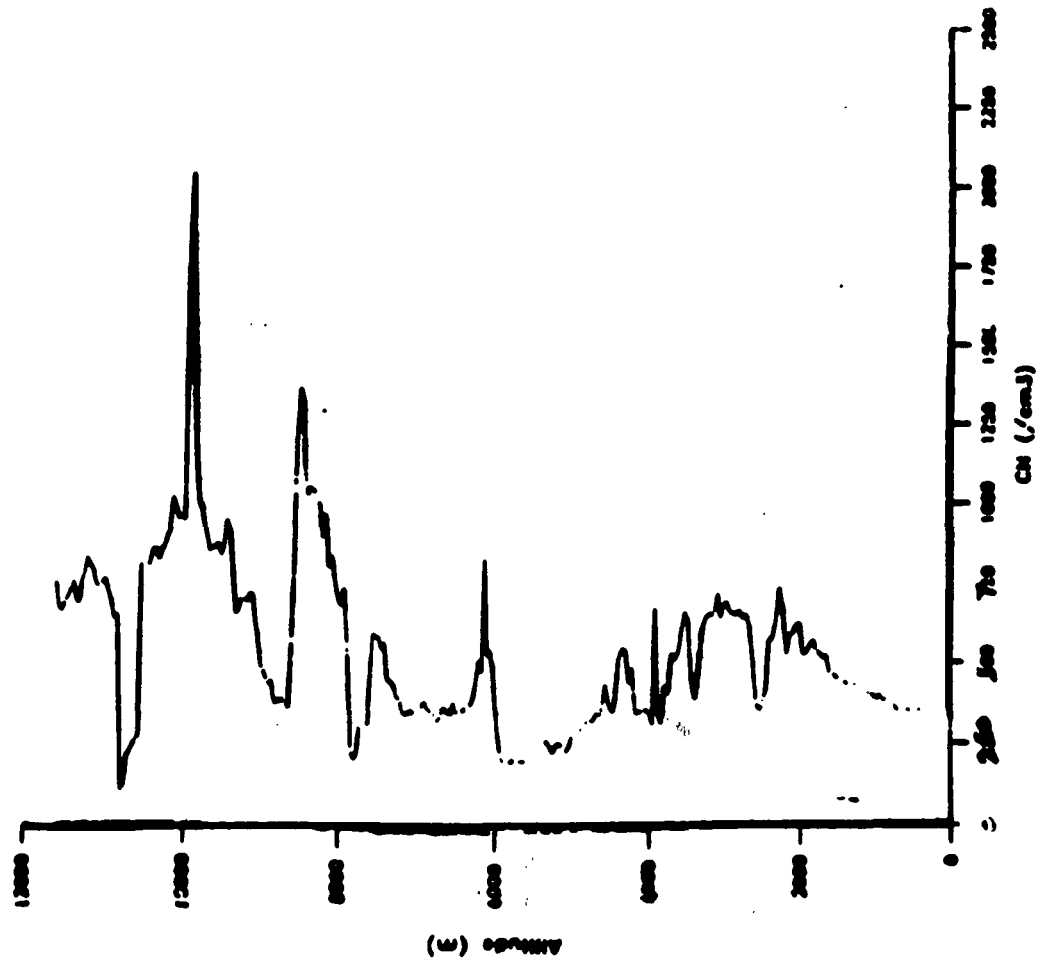


Figure 4: Total particle concentration at 11 km altitude over the tropical Pacific during TOGA-COARE. This was a horizontal penetration of a tropical cyclone. The lower concentrations during the penetration were due to heating of the sample for particle volatility determinations.

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Flight 116 CN vs. Altitude

26.12-26.60 Hours February 20, 1993



Flight 116 Temperature vs. Altitude

26.12-26.60 Hours February 20, 1993

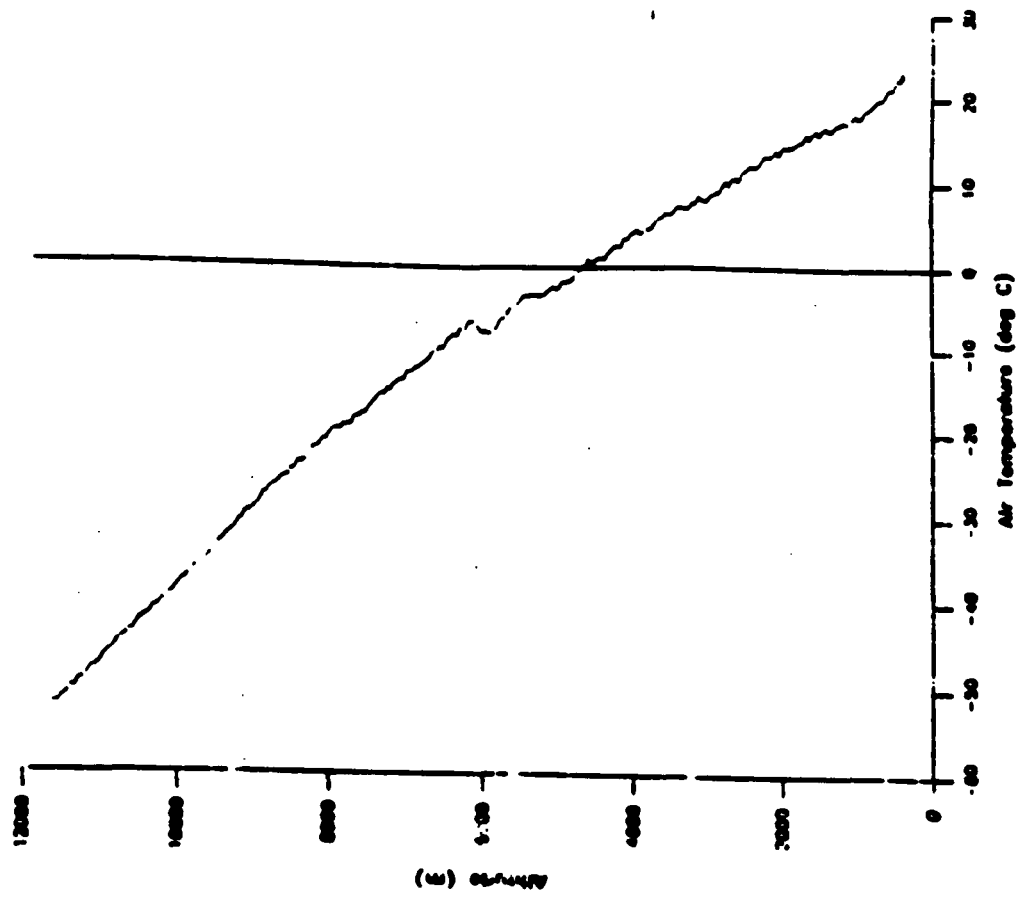


Figure 5: CN particle over TOGA COARE area show maximum at about 10 km, 2000 cm^{-3} , showing no relation to stable layers.

Flight 118 CN Counts vs. Altitude

2.3-3.0 Hours February 24, 1993

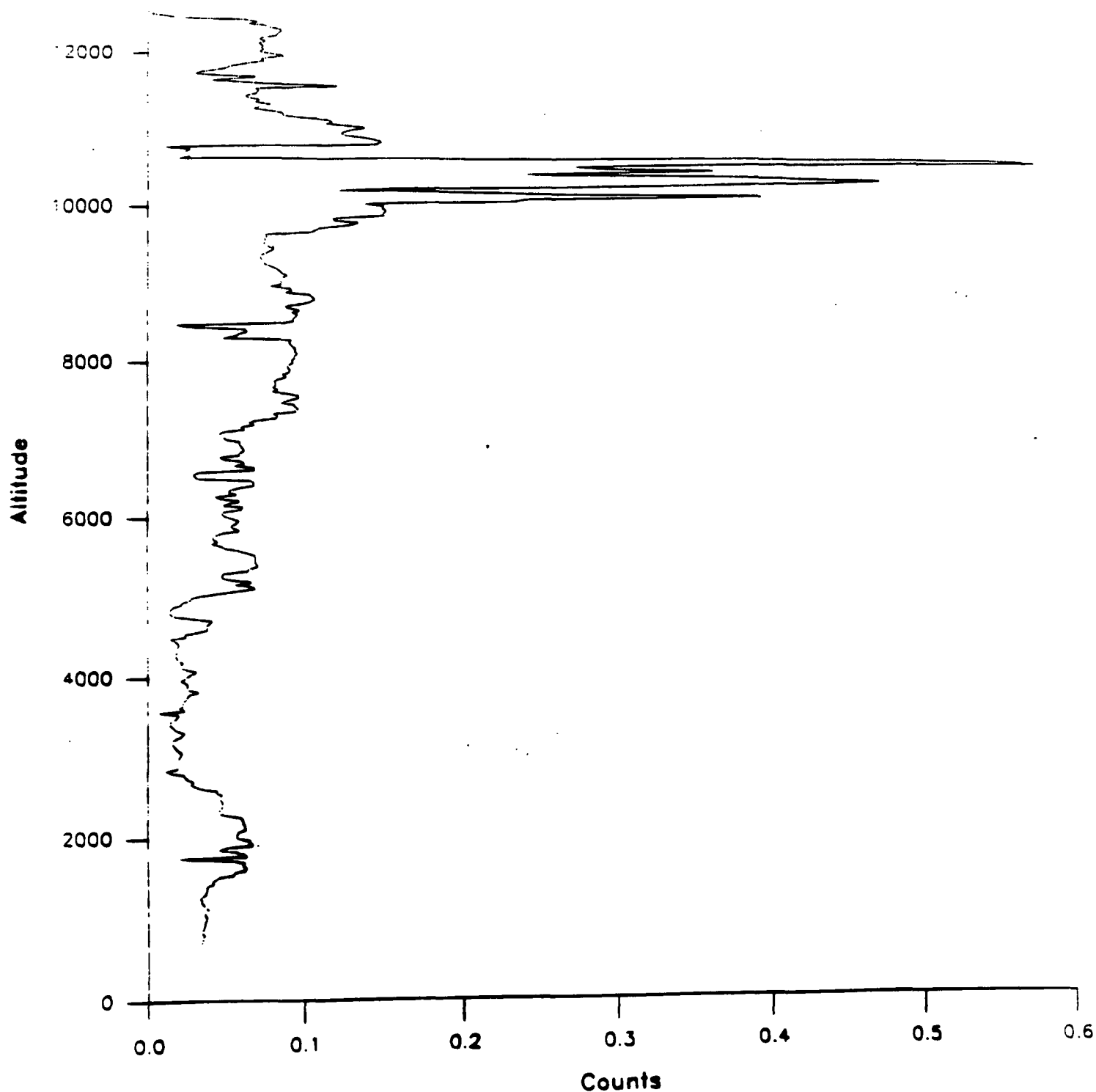


Figure 6: A similar profile to (Fig. 5) under different conditions.

FLIGHT 120
FEBRUARY 29 1993

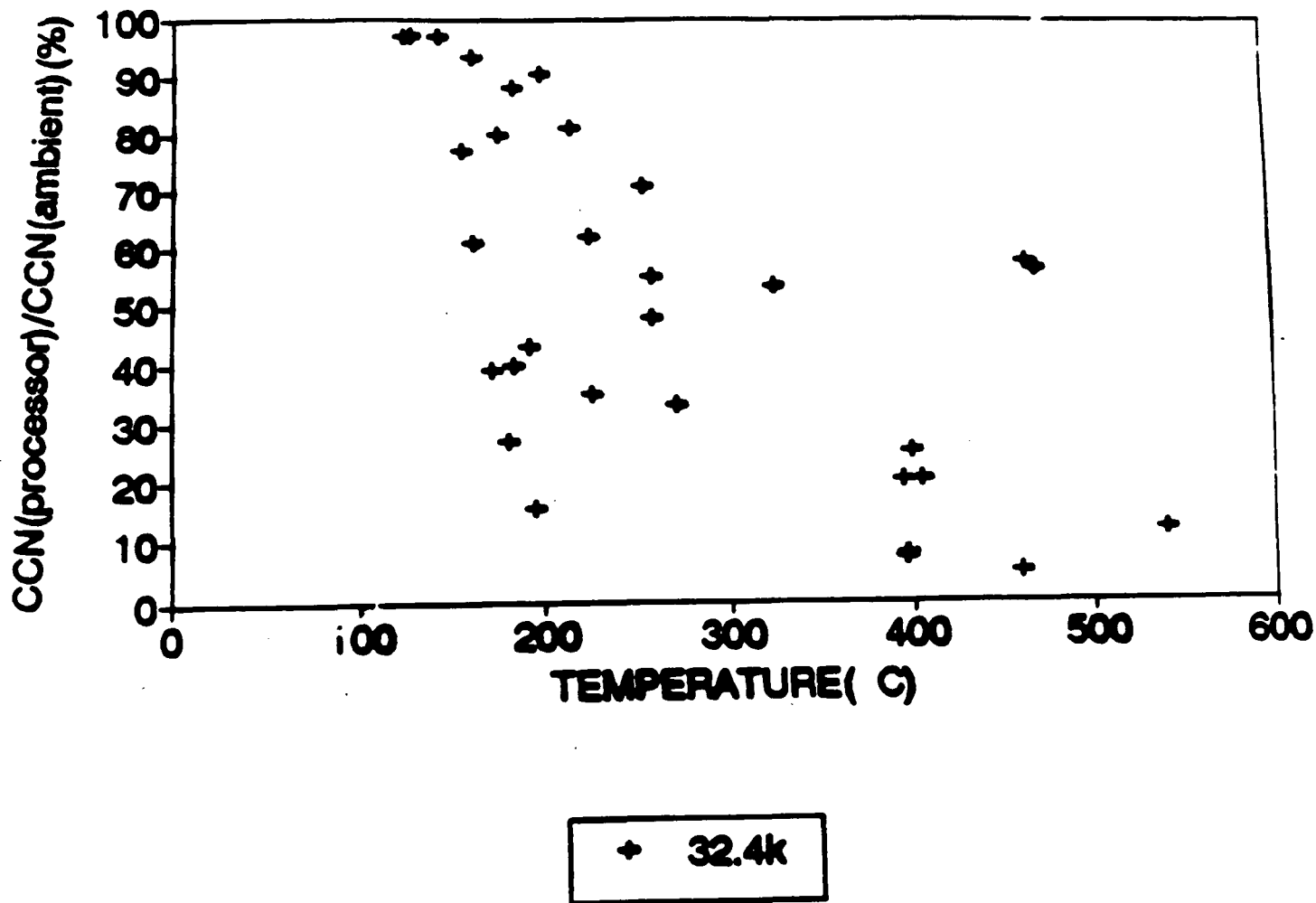


Figure 7: Spread of processed/unprocessed related to temperature. All data 32,400 ft. Particles do not completely disappear even at 500°C, suggesting a refractory component.

FEBRUARY 11 1993
H: 29-33k feet

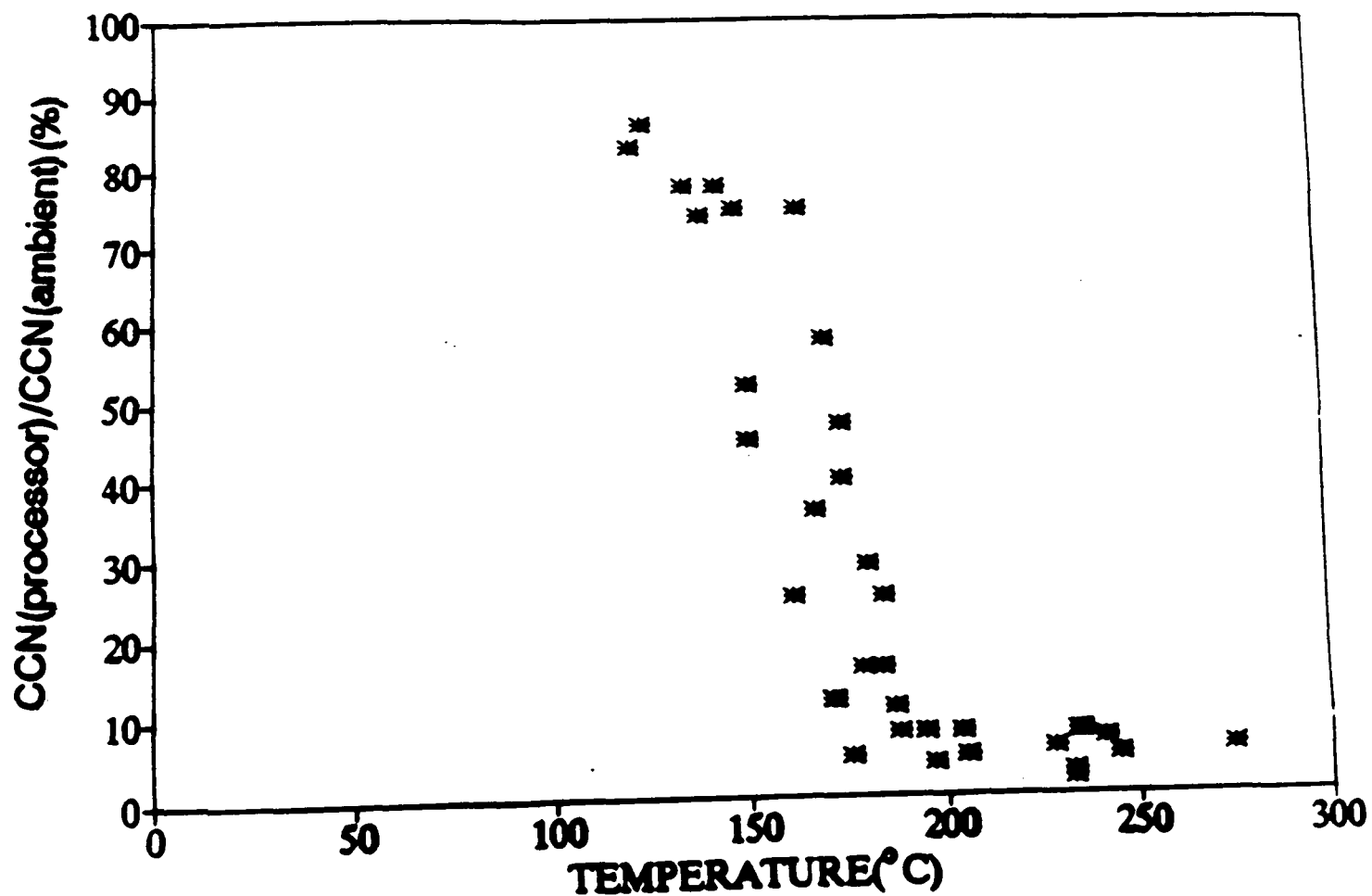


Figure 8: A sample over about 30 min time showing particles with similar behavior disappearing at 160°C.

FLIGHT 118
FEBRUARY 24 1993

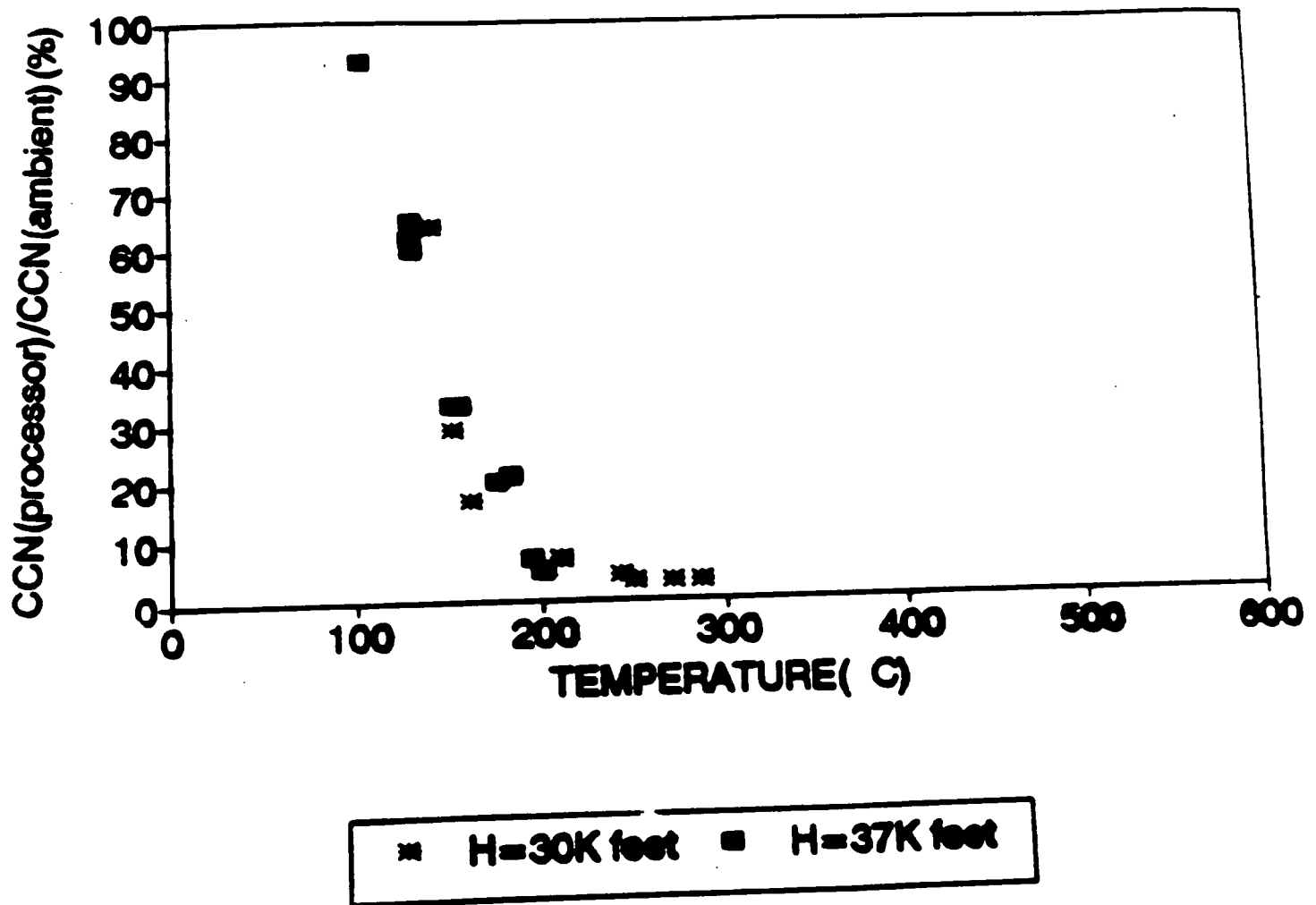


Figure 9: Cases where aerosol at two levels show similar behavior.

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FLIGHT 111
FEBRUARY 5 1993

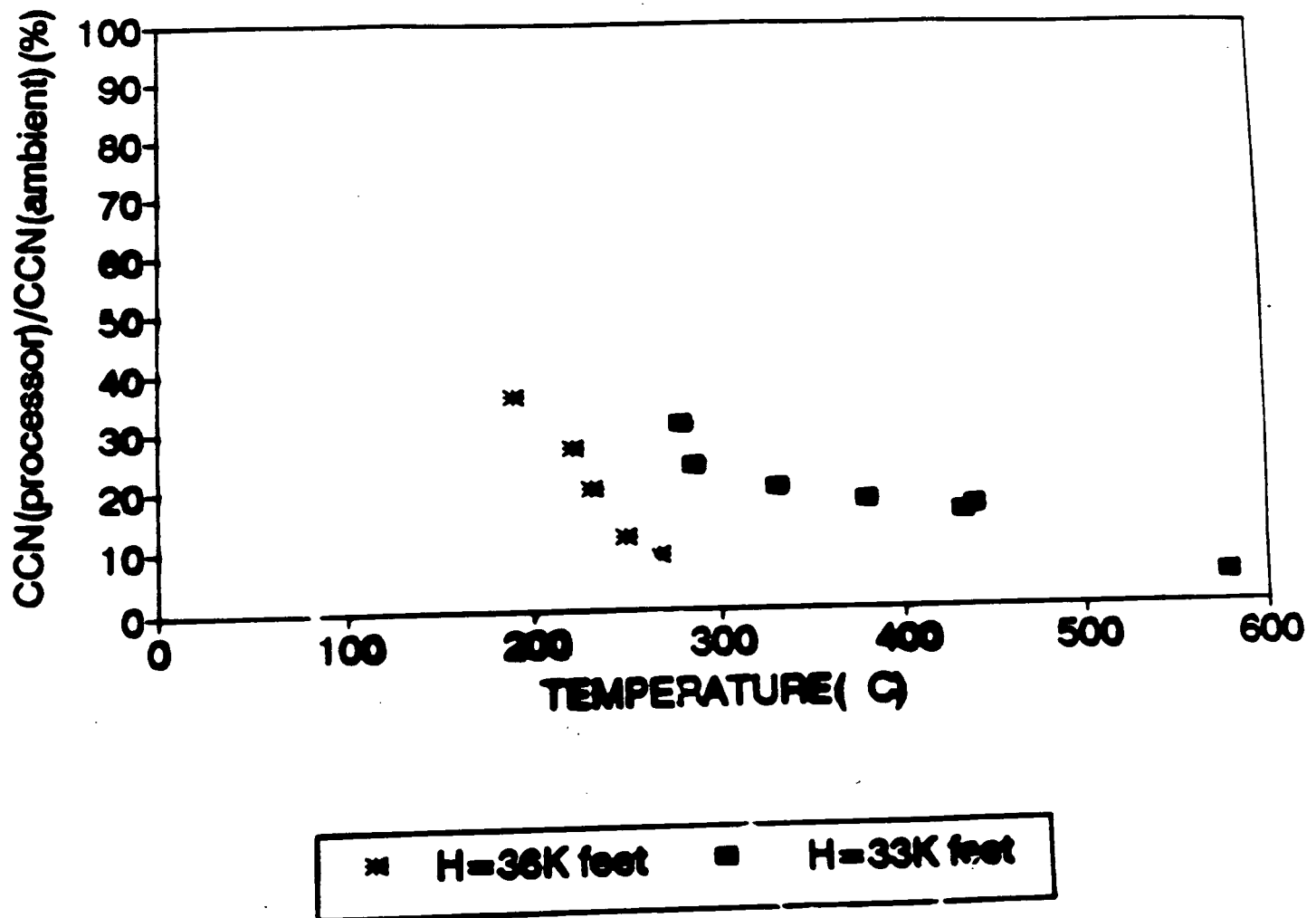
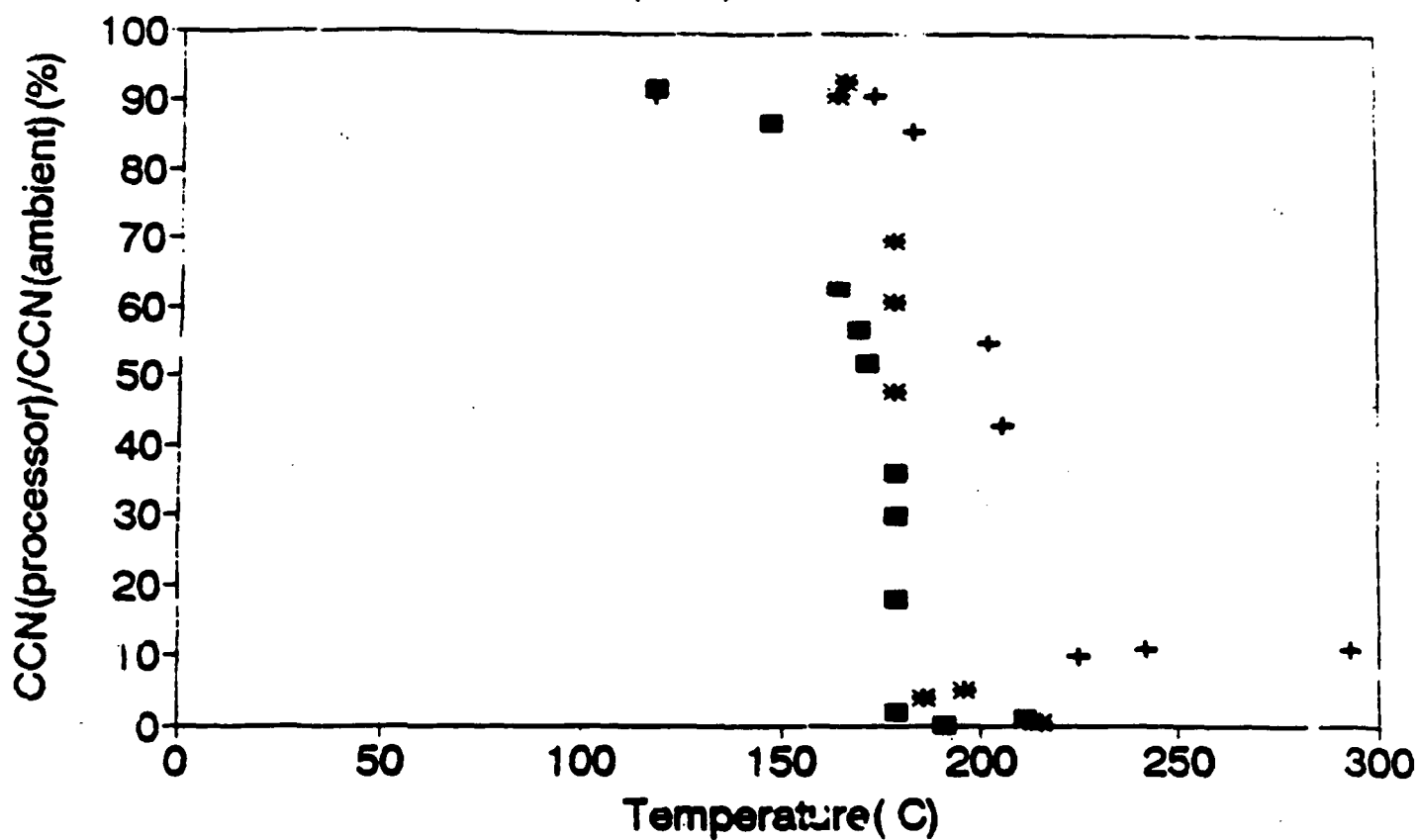


Figure 10: Cases where two levels differ widely.

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November 18, 1993
(NH₄)₂SO₄



+ D= 0.20um Sc=0.053% * D=0.062um Sc=0.28% ■ D=0.025um Sc=1.19%

Figure 11: Laboratory study of ammonium sulfate particles for comparison, showing that larger particle sizes disappear at require to slightly higher temperature for evaporation (p

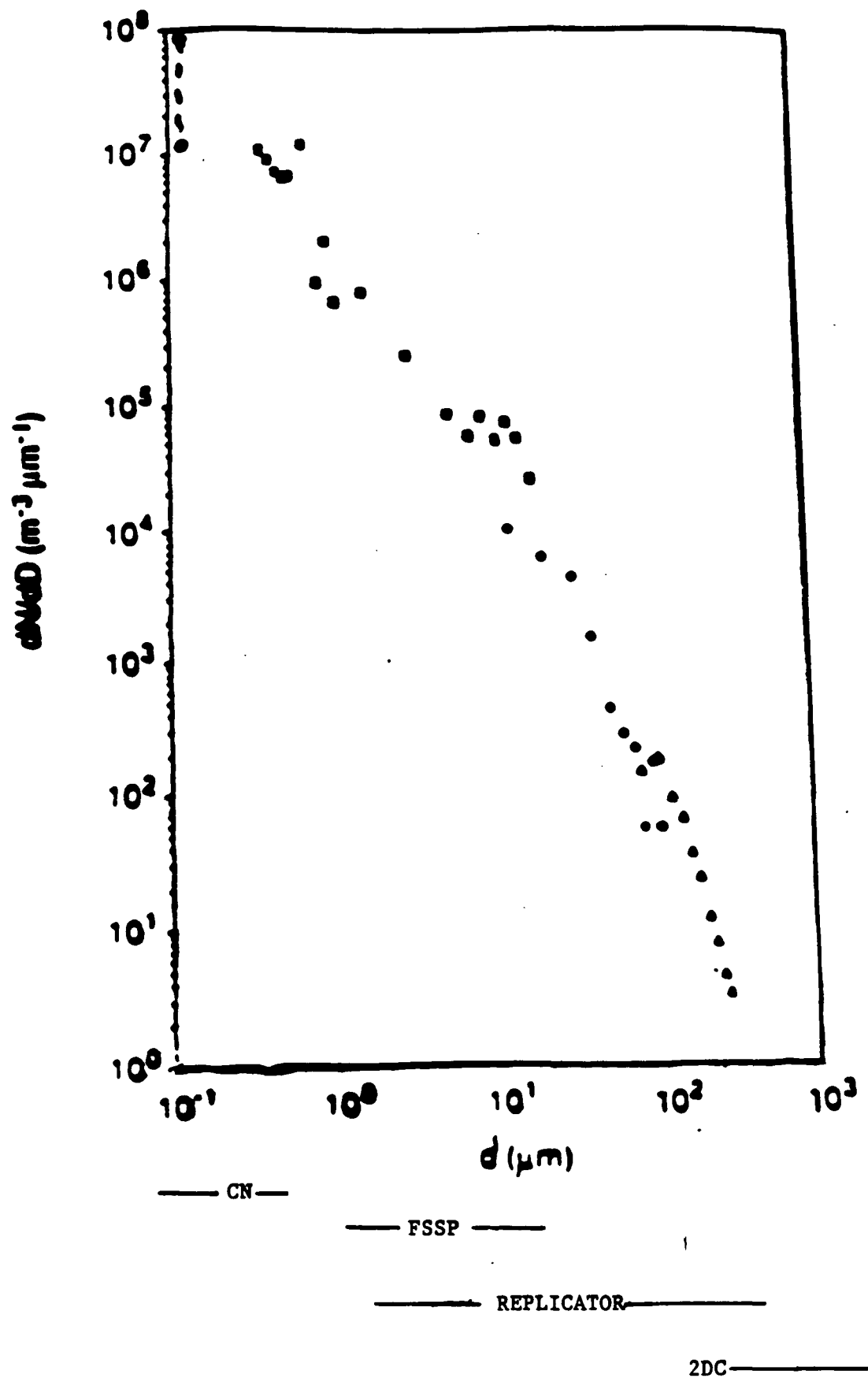


Figure 12: Composite spectra of particles from all instruments:

- CN (small)
- FSSP ($10 \mu\text{m}$)
- Replicator ($10 - 100 \mu\text{m}$)
- 2DC ($> 100 \mu\text{m}$)

Ammonium Sulfate

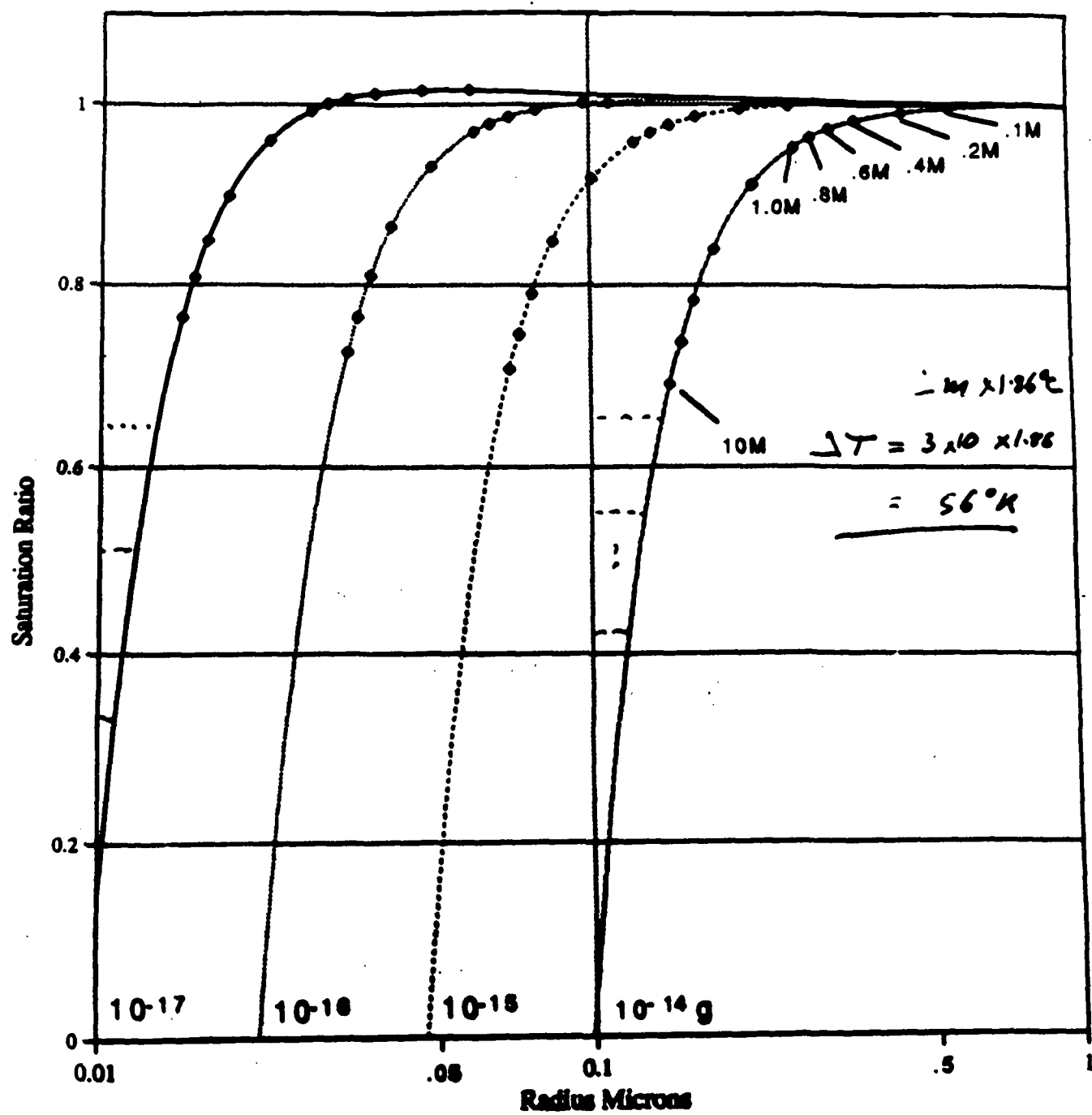


Figure 13: Köhler curves showing iso-depression points for equilibrium melting point.

PART B: AUTOMATED ANALYSIS OF AIRCRAFT ICE PARTICLE DATA

The digital image analysis system for automation of replicator data analysis was supported by NASA's FIRE 2 program. W. Patrick Arnott was the principal investigator, John Hallett coprincipal investigator, technical support was from Rick Purcell and Paul Lage of DRI, and software development support was from Mark Turner (Atmospheric Science graduate student) and Steve Nerad (Electrical Engineering undergrad). Ivan Gibbs (Physics Department undergrad) currently is working on the project analyzing data. A description is given of the system to automate analysis of formvar replicator data using digital image analysis and computer control of film advance. The formvar replicator data supplies number concentrations and habit information for ice crystals and cloud droplets simultaneously ($5\text{ }\mu\text{m} < D < 800\text{ }\mu\text{m}$, where D is particle maximum dimension) in cirrus and mixed phase clouds. It is possible to differentiate between liquid drops and spherical ice particles by the nature of the images. Crystal replica can be imaged at much higher resolution than with other optical probes such as the Particle Measuring System 2DC probes.

The main product of our efforts is characterization of cirrus clouds from the view point of small crystals ($< 200\text{ }\mu\text{m}$) and their radiative and microphysical significance. We currently are analyzing a number of case studies involving data from FIRE, TOGA-COARE, and other cirrus field studies; to find out where small ice crystals are prevalent; to determine their numbers, sizes, crystalline forms, and growth environments; and to assess the accuracy and utility of PMS probes (2DC, FSSP) for measuring cirrus properties. The frequency of occurrence of bimodal spectra is important in assessing cloud radiative properties.

1. Hardware

Figure 1 is a video photograph of the system for automated analysis of replicator data, except for the computer. Raw replicator data to be analyzed is placed in the reel on the right of the figure. A stepper motor and slip clutch (not shown) would rotate the data supply reel in a clockwise sense when the clutch is not slipping; otherwise, this stepper motor only supplies tension to the replicator film. Movement of the replicator film (either toward or away from the data supply) is controlled by the film transport. The computer interface for the film transport is barely visible behind the microscope. Replicator film is imaged, possibly under a variety of magnifications, using the microscope and video camera. The fiber optic illuminator for the microscope is shown in the rear. The replicator data take up reel is also equipped with a stepper motor and slip clutch to keep the film tight. The joystick controls for microscope y axis position and focus is on the left.

Figure 2 shows the user station for analyzing replicator data. The video monitor is useful for focusing the microscope while the computer is busy printing or writing data to disk. The user interacts with the system by input through the keyboard, computer mouse, and the proportional (the farther you push, the faster the motors run) joysticks for focus and y axis position control. The computer with frame grabber, and the printer, are not shown, and are on the lower shelf of the table. In routine operation the user can control all aspects of the system hardware shown in Fig. 1 using the computer and the joystick controls.

Figure 3 shows the film transport system in more detail than in Fig. 1. The stepper motors are interfaced to the computer through the stepper motor control box. The frame grabber on the computer has both a bnc connector for video input and 4 lines of digital output for stepper motor position control. The replicator supply reel is equipped with a stepper motor and slip clutch to keep the film under tension. Figure 4 shows a more detailed view of the film transport. The film is threaded through the lower idler arms, and over a fixed radius roller equipped with extended nubs that push through the film sprocket holes. It is vital to note that each stepper motor pulse moves the film a fixed, known distance, so that one may convert film position in meters to aircraft position in cloud. Data from the aircraft position is loaded into the software for performing this conversion.

Figure 5 shows the detailed microscope arrangement. The specifications for each lens, and for the pms 2DC probe used on the University of North Dakota Citation aircraft are as follows:

<u>Objective</u>	<u>Resolution (pixels/μm)</u>	<u>Field of View ($\mu\text{m} \times \mu\text{m}$)</u>	<u>Working Distance (cm)</u>
1x	0.1745	3667x2750	12.9
2x	0.3265	1960x1470	5.4
3.5x	0.5647	1133x850	2.4
5x	0.9600	667x500	1.7
PMS 2DC	0.0303	1056x1056	n/a

The reciprocal of resolution is the number of microns spanned per pixel in the image, where the frame grabber digitizes images with 640x480 pixels per picture. For example, the 1x objective should barely resolve a crystal with $\approx 6 \mu\text{m}$ diameter, and the 5x objective should barely resolve a crystal with $\approx 1 \mu\text{m}$ diameter. As resolution increases, the field of view (actual area of the replicator film viewed) decreases. Large field of view is desirable to minimize analysis time. We usually use the 2x objective since it gives a reasonable trade-off of large field of view for lower resolution. Note that the 2x objective gives us a better field of view than the PMS 2DC probe, and about ten times the resolution.

Denote by:

N = number of crystals per liter in the cloud (the desired quantity);

n = number of crystals per area in the microscope field of view (the measured quantity);

f_s = replicator film speed during data acquisition;

a_s = aircraft speed during acquisition;

w = replicator slit width parallel to the direction of travel of the replicator film.

Typical values are $f_s = 7.62$ cm/sec, $a_s = 110$ m/s, and $w = 2.5$ mm. Then

$$N = n f_s / (a_s w) \quad , \quad (1)$$

is the number of crystal per liter in the cloud. For example, if there is one crystal in the field of view of the 2x objective, and we use the typical values, then $N \approx 96$ crystals / Li. Typical values are $N \approx 100$ to 500 / Li for crystals less than $25 \mu\text{m}$, so we might expect 1 to 5 crystals per field of view using the 2x objective. The spatial resolution of the replicator data (in the cloud) is denoted by S_r and is given by

$$S_r = a_s w / f_s \quad . \quad (2)$$

The range of S_r is thus $S_r \approx (0.9 \text{ m to } 7.2 \text{ m})$. Only the 1x objective has a field of view along x greater than w . Thus for all other objectives, the spatial resolution of changes in cirrus cloud properties as measured by the replicator, and analyzed by the automated system, is given by Eq. (2). Note that since the spatial resolution of the film transport stepper motor is $304.6 \mu\text{m}$ per step, the stepper motor resolution does not hinder the overall spatial resolution of the system.

Figure 6 shows the proportional joystick control box for adjusting film y position and microscope focus. Cables from this box are connected to DC motors on the microscope to perform focusing and y axis position adjustment. Left-right motion of the joysticks moves the microscope stage in-out, and up-down. The farther the joystick is pushed from equilibrium, the faster the DC motors turn.

2. Software and system operation

Film advance and frame counting are entirely under computer control with use of the National Instruments Lab View program and the CONCEPT VI GTFS frame grabber I/O driver. Data files supplying time resolved replicator tape count, aircraft speed, altitude, latitude, longitude, and air temperature are read by the Lab View program, and are used, in part, to compute the replicator sample volume. The National Instruments LAB VIEW programming environment is used for controlling all aspects of the automated replicator analysis system. This programming language is largely symbolic, with Virtual Instruments (VI's) that are connected by wires. VI's are like traditional subroutines used by languages such as FORTRAN, and wires are analogous to variables passed between subroutines. The programmer obtains an immediate appreciation of program flow when viewing the wiring diagram in this type of programming. The CONCEPT VI GTSF software contains the driver for the SCION framegrabber card, and also performs digital image analysis. The user of LAB VIEW VI's operates a software instrument with buttons, toggles, graphs, switches, etc, that performs the intended function.

Two modes of operation have been developed, partial and fully automatic analysis. In fully automatic mode the user only inputs the time to analyze replicator tape from, loads the replicator tape on the system, and returns later to retrieve the results. We found this mode to be unreliable because we could not train the system to discard artifact. In other words, the automatic mode counts everything! We attempted to make an algorithm that would allow the computer to make the same decisions a human observer would as to what is and is not a crystal, but were not successful in achieving the high quality data analysis needed. This mode of analysis is usable in specific sections of film with low artifact and modest spread of particle shapes. However, future research will include some study of using a human trainable neural net to develop a more robust algorithm the computer can use to fully automate analysis. Artifacts arise because the raw replicator film itself has imperfections that can look like crystals, because the formvar occasionally has grit in it and can lead to linear scratches, and because the process of formvar application to the film sometimes leads to smearing or bubble formation.

In partial automatic analysis, the user makes the final decision on what is and is not a particle. The computer handles all the work of keeping track of film position, and hence the time and location in cloud. The user typically starts with a new frame showing some crystals and some artifact. When surface dirt abounds, the user will clean the replicator film with distilled water and optical lint-free cleaning paper. Then the user will use the computer mouse to click on particles. The computer notices a click has been made and then analyzes the particle. Specifically, the algorithm determines the maximum dimension of the particle and its projected area. Once the user has clicked on all particles appearing on the screen, he uses the mouse to click on the button for next frame. The algorithm detects the next frame click and moves the film with aid of the stepper motor to the next frame. Careful partial analysis mode of operation is the most accurate and hence most desirable technique. New users of the system can be taught about artifact by viewing formvar coated film that definitely has no crystals, then viewing our laboratory replica, then viewing actual replica both before and after cleaning the film. Ice crystals have hexagonal or rectangular symmetry, so the user can use obvious symmetry as a guide. However, not all crystals in the atmosphere have perfect symmetry, and sometimes crystals in an evaporating cloud are somewhat rounded, so the user must be aware of all possibilities. Artifact from the break up of a large crystal is usually not a problem to identify because fragments are scattered near the parent crystal and frequently look like a part of the 'jigsaw puzzle.' Besides, the real usefulness of replicator analysis lies in studying portions of cloud where the PMS 2DC is not doing an adequate job. A case study is given below to illustrate some of the points concerning artifact.

3. System specifications

a. RECENT REFERENCE FROM FIRE II ANALYSIS: W. Patrick Arnott, Ya Yi Dong, John Hallett, and Michael R. Poellot, 1994: Role of small ice crystals in radiative properties of cirrus: A case study, FIRE II, November 22, 1991. J. Geophysical Research vol 99, no. D, pages 1371-1381. This reference describes the type of analysis we can perform, though results reported therein were not obtained with the automated system.

b. REPLICATOR DATA: Replicator data is collected on 16 mm film by coating the film with formvar and exposing it to the airstream from either an aircraft window, or from a wing mounted PMS pod. Particles smaller than 10 μm can be routinely and reliably identified with use of microscopy. Replicator derived size distributions are vital for crystals with maximum dimension in the size range $10 \mu\text{m} < D < 200 \mu\text{m}$, where PMS data is either totally lacking, or of poor resolution. PMS data is often sufficient for deriving size and projected area distributions for particles larger than 200 μm , but is often not sufficient for crystal habit identification. Though replicator data yields size distributions for particles larger than 200 μm , the chief advantage of the data for larger particles is in the fine detail that can be achieved for identifying crystal habit and assessing when aggregation has occurred. Replicator film speeds vary from 0.5 cm/s to 61 cm/s.

c. IMAGE DIGITIZATION: 640*480 pixel resolution frame grabber card.

d. RESOLUTION: 0.3265 pixels/ μm resolution nominal, though adjustable through use of other microscope objectives. (Compare: The PMS probe flown on the CITATION has only 0.0303 pixels/ μm resolution.)

e. FIELD OF VIEW: 1960 μm x 1470 μm nominal, though adjustable through use of other objectives. (Compare: The PMS probe flown on the CITATION has 1056 μm x 1056 μm field of view.)

f. MOTORIZED CONTROL OF FILM POSITION: Frame grabber card has digital I/O that is used for stepper motor control for accurately determining position on the replicator film. Position on film is translated to aircraft time by use of aircraft state data and interpolation. Stepper motors control position along the film length, and DC motors control both the microscope y-axis position and focus so the user can effectively analyze data without having to physically get up and tweak the microscope. Stepper motor advances the film 304.6 μm per step.

g. DIGITAL IMAGE ANALYSIS: Digital image analysis is used to measure crystal maximum dimension and projected area. Each crystal must be accepted/declined by one click of the mouse so that the element of human decision makes the final choice on which crystals are counted.

h. NOMINAL SIZE BINS: Size bins are 0-25 μm , 25-50 μm , ..., 475-500 μm . The number per liter in each bin is counted, along with the projected area of each crystal. Number and dimensions of size bins are user selectable.

i. HARDCOPY OF CRYSTAL IMAGES: Individual crystal images can be saved or discarded, and can be printed along with a scale indicating size, and with the pertinent aircraft state data - lat, long, air temp, height, and aircraft time.

j. FURTHER PROCESSING OF PMS AND REPLICATOR DATA AVAILABLE: We can also estimate:

- crystal mass by use of mass dimension relations once crystal habit has been identified from replicator data,
- Mass dimension relations will also be derived using cloud scope data,
- Total concentration in #/Liter,
- The mean crystal diameter as a function of time,
- Total projected crystal area / Liter, (useful in computing extinction and other radiative properties).

4. Example Data Set.

On December 5, 1991, from 19:02:00 to 19:03:00, the University of North Dakota Citation aircraft was located at the top of a cirrus cloud. The altitude and air temperature are shown in Fig. 7a, and the aircraft trajectory is shown in Fig. 7b. The PMS 2DC probe was not registering any particles, so if there were any ice crystals present, they had to have maximum dimensions less than 66 μm . The PMS FSSP probe was registering particles, though since this probe does not directly image them, the exact type and size is uncertain. Our example data set was motivated by a desire to provide size spectra for comparison with the FSSP probe, and to get an idea of the particle concentration at this location. One minute of in cloud analysis takes one week to for the careful user to analyze, though automated analysis of more uniform replica lacking defects is accomplished in 3 hours.

Figure 8a shows the total concentration as a function of time, with a peak of 9 particles per liter near 19:02:10. While 9 small particles per liter certainly does not constitute a high concentration, taking into account the small particles is especially necessary because they efficiently scatter solar wavelengths per unit ice mass, and are imperfect absorbers, emitters, and attenuators of thermal IR wavelengths. The computed mean crystal diameter and visible extinction coefficient are shown in Fig. 8b. The maximum mean diameter of 60 μm occurred near 19:02:10. The visible extinction coefficient is quite low (we are looking at an optically thin portion of the cloud), with maxima near 0.013 km^{-1} near 19:02:10 and 19:02:40. Figure 9a shows the time and size resolved number concentration. Note that the peak concentration

occurred near 19:02:10, and corresponded to about 35 μm maximum dimension crystals. Figure 9b shows the corresponding area concentration. These distributions are very similar in form because the size distributions were fairly monodisperse.

Figures 10 through 17 are arranged chronologically from near 19:02:00 to near 19:03:00. Time on the figures is given as GCT in the hours:minutes:seconds format, in seconds from midnight in the seconds format, position refers to the physical location of on the replicator film, sample volume is the combined microscope and replicator sample volume for the image, and the remaining elements are straightforward. Crystal size can be determined relative to the 100 μm scale. These figures illustrate some crystals as well as the background artifact that the system user must contend with. For example, the crystal in Figure 10 has radial symmetry, while the other entities do not. Note that there are several scratches in the formvar arising from its application to the film or a grit particle on the track. The other entities in Fig. 10 which look somewhat like particles are similar to artifact one sees on film not exposed to particles. Fig. 11 shows a column crystal that was counted, and a large black speck that was not. Note also the fiber on the lower right. Figure 13 shows 2 hex plates and the formvar splash they made when they landed on the film. Figure 15 shows a crystal that looks something like a triangle, and two particles that were added to the film during the cleaning process. The triangle in Fig. 15 could not be removed by cleaning, and further cleaning removed the 'dirt'. Figures 16 and 17 show small and larger plates. It should be noted that the film is more readily evaluated on the computer screen and video monitor than on paper.

Future improvement of replica analysis time and quality can only be achieved through careful cleaning of the raw formvar and film prior to flight and through careful handling after flight to avoid the introduction of dirt.

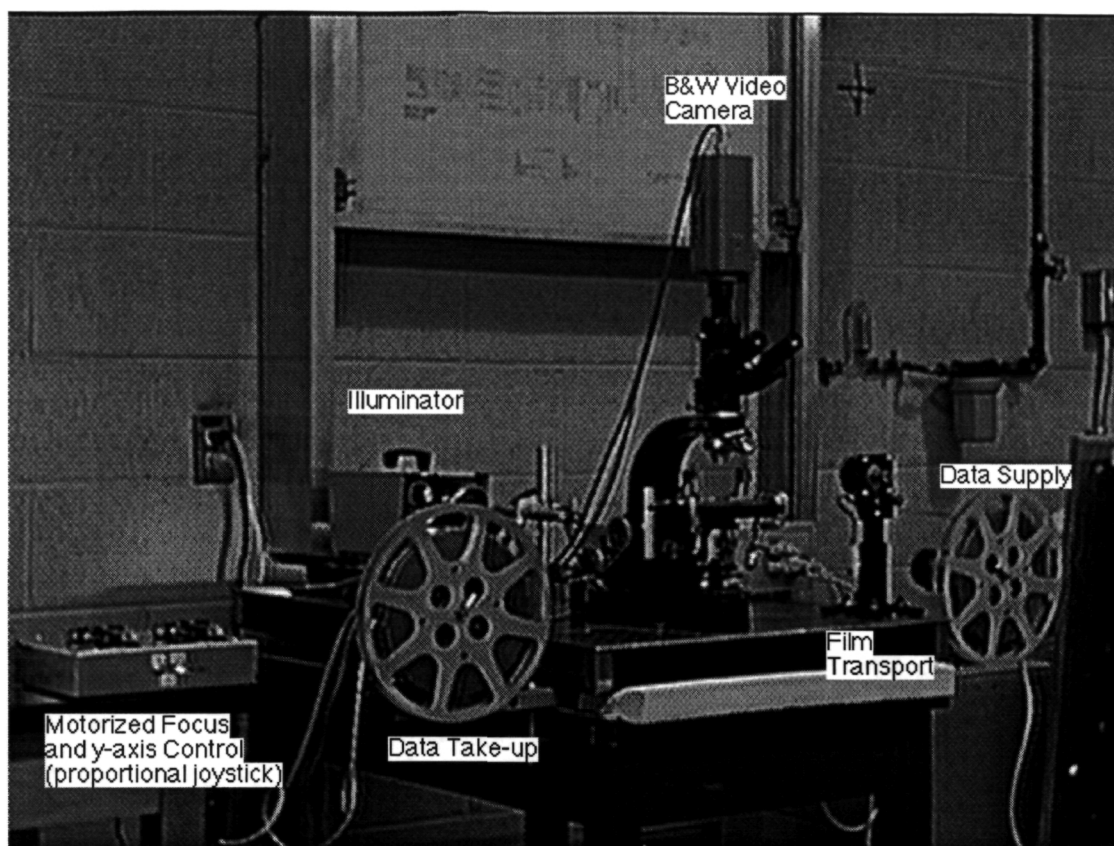


Figure 1. Overall view of the system hardware, except for the computer.

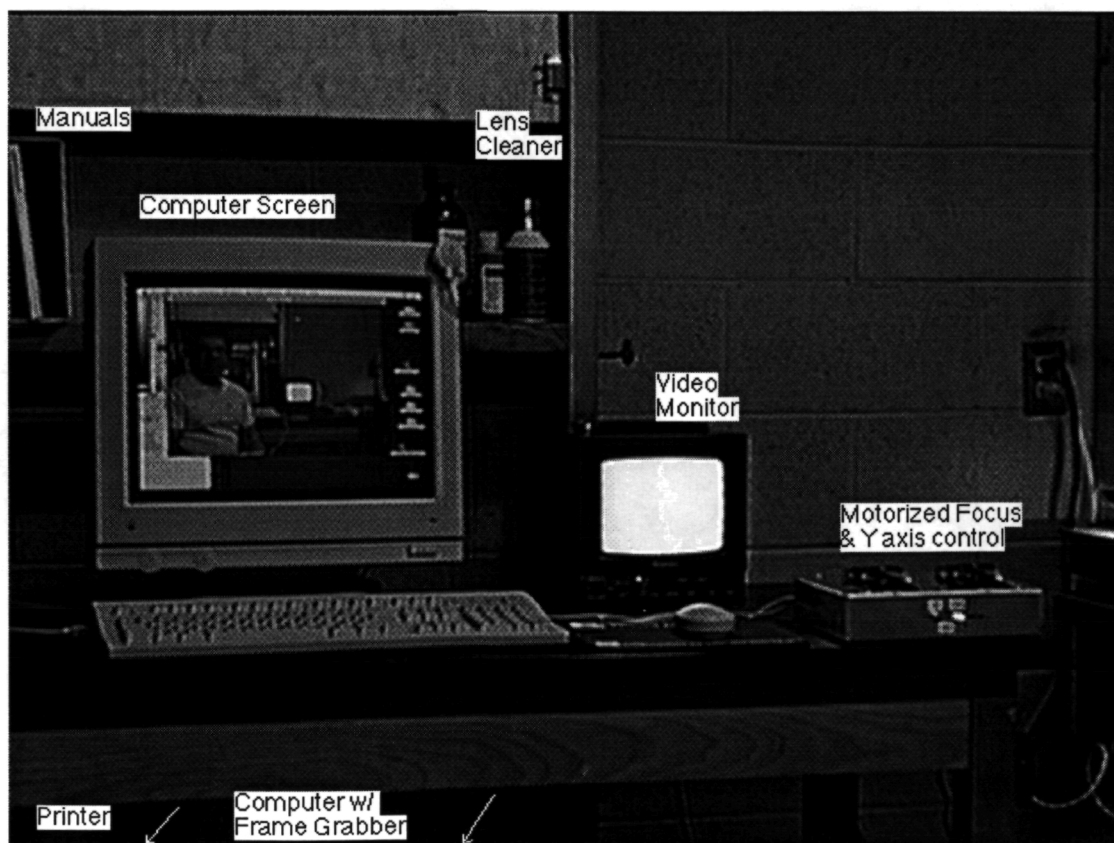


Figure 2. Overall view of the computer arrangement. Note that user input to the replicator analysis system occurs through the keyboard, mouse, and proportional joysticks for focusing and y axis control.

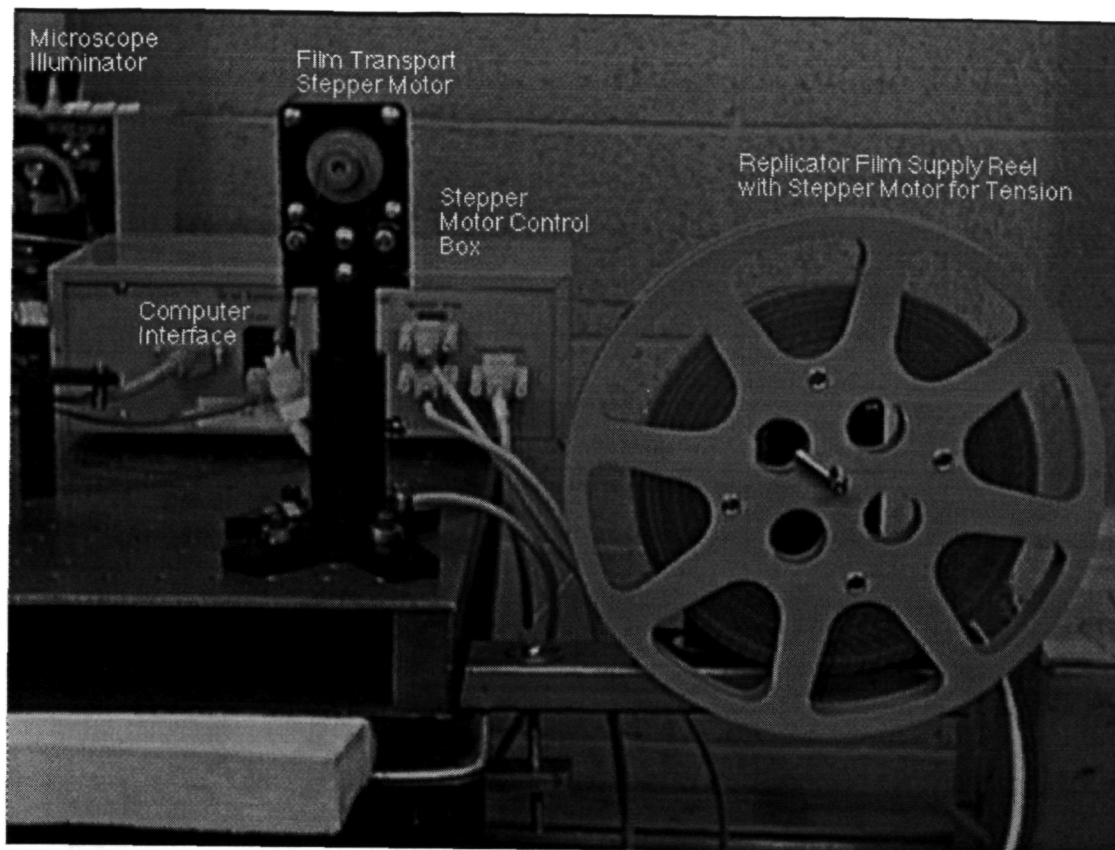


Figure 3. More detailed view of the film transport.

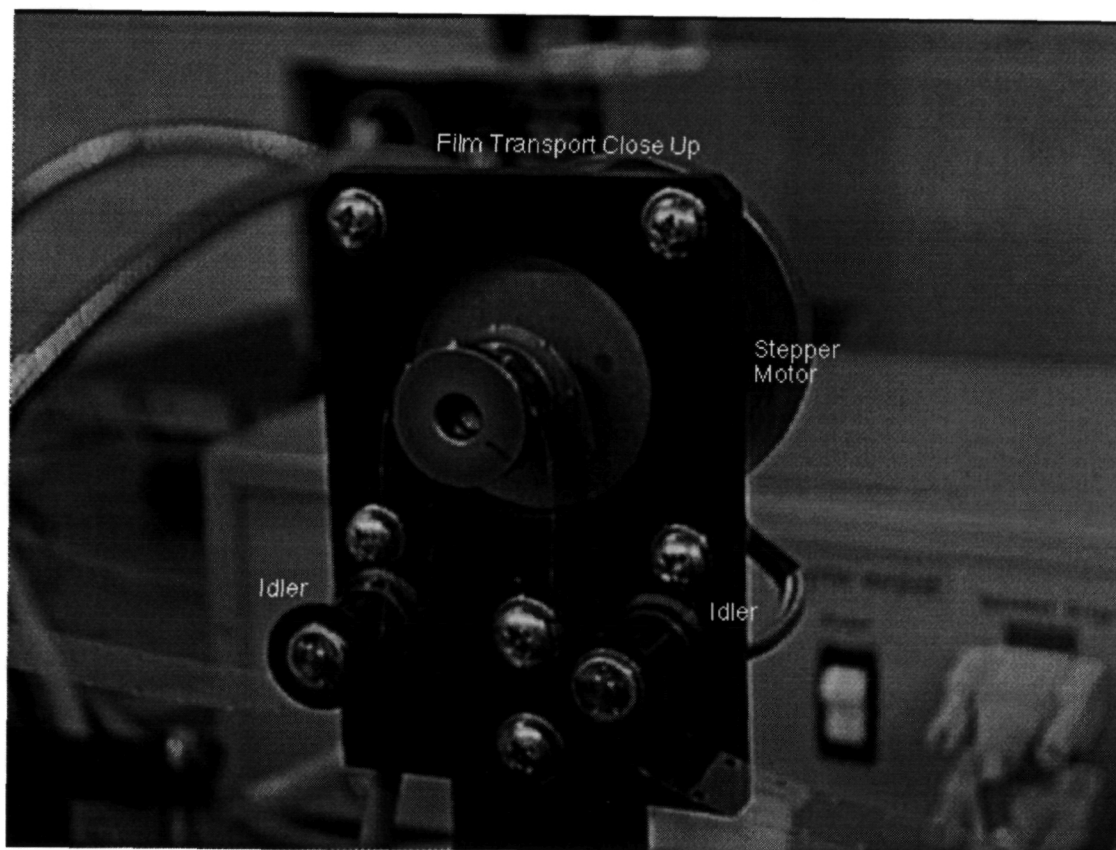


Figure 4. Detailed view of the film transport. A stepper motor is mounted on the reverse side.

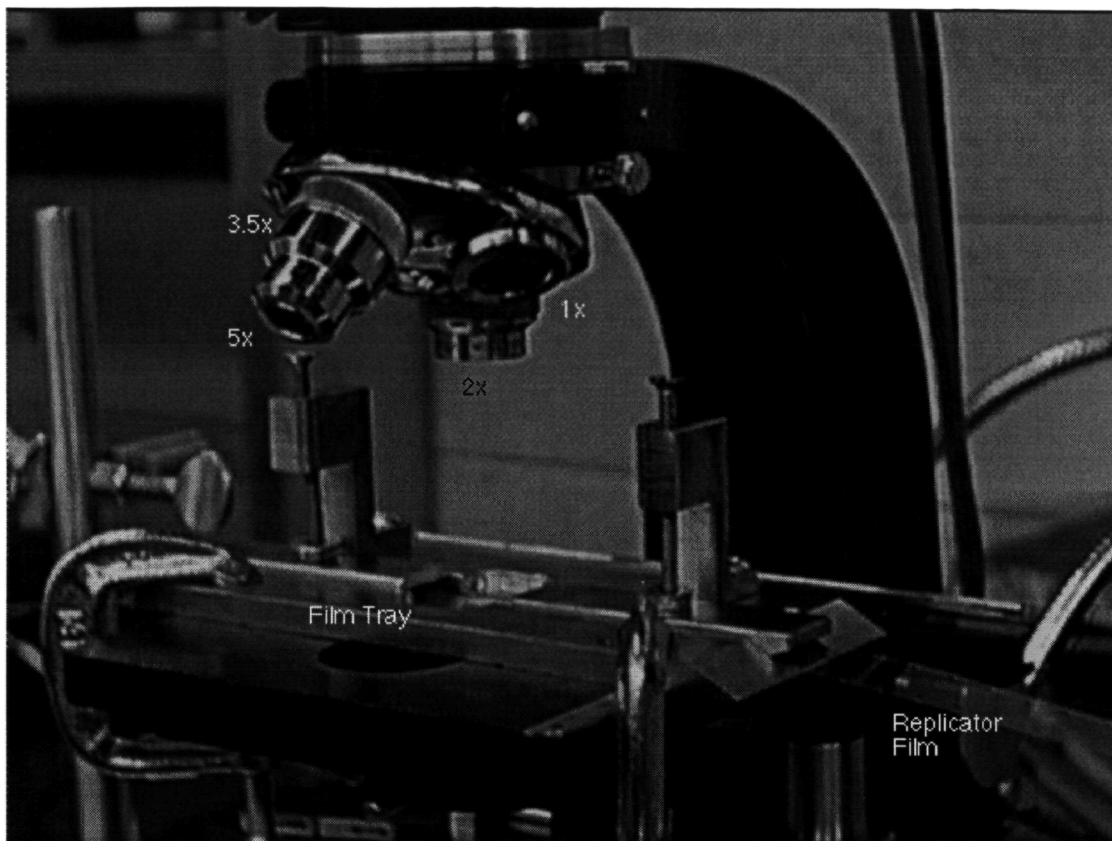


Figure 5. Detailed view of the microscope. Film is transported along the x direction by the stepper motor shown in figure 4. Film motion perpendicular to x is controlled using one of the joysticks in figure 6 and a DC motor mounted under the microscope stage. Focus is achieved using the other joystick in figure 6 and a DC motor mounted on the microscope body.

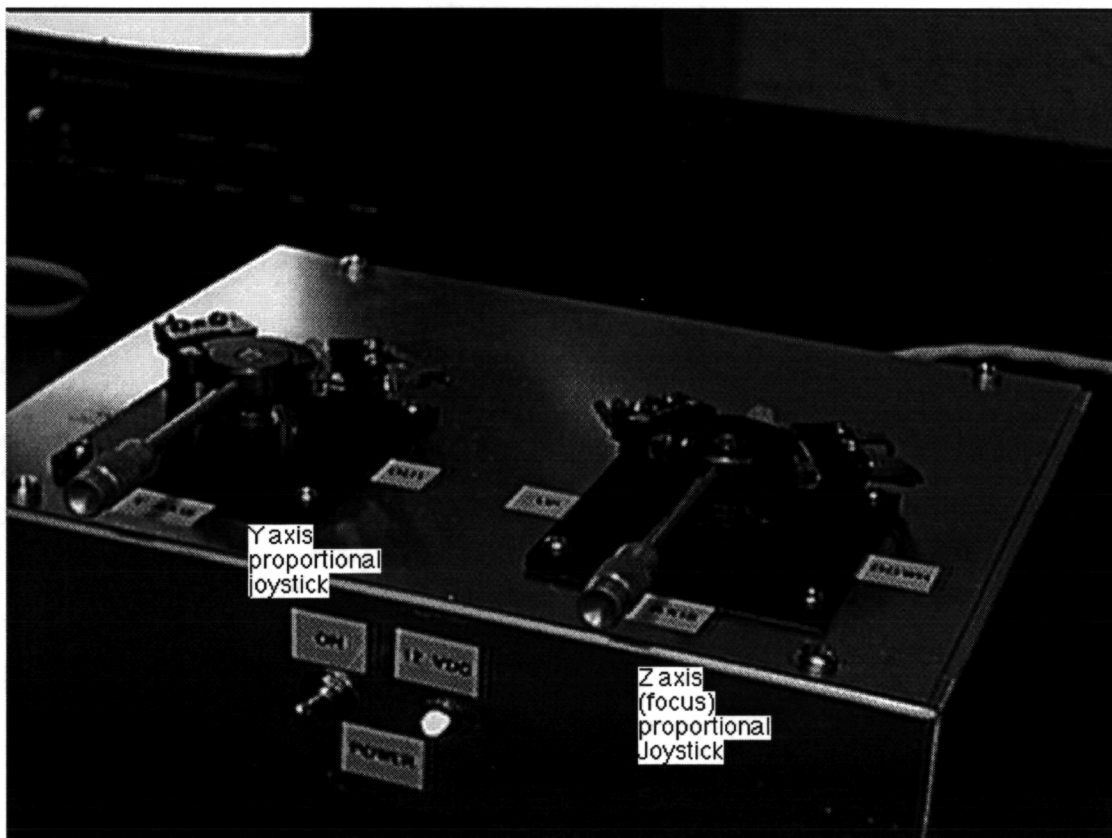


Figure 6. Joysticks used to focus the microscope and to control the y position of the replicator film.

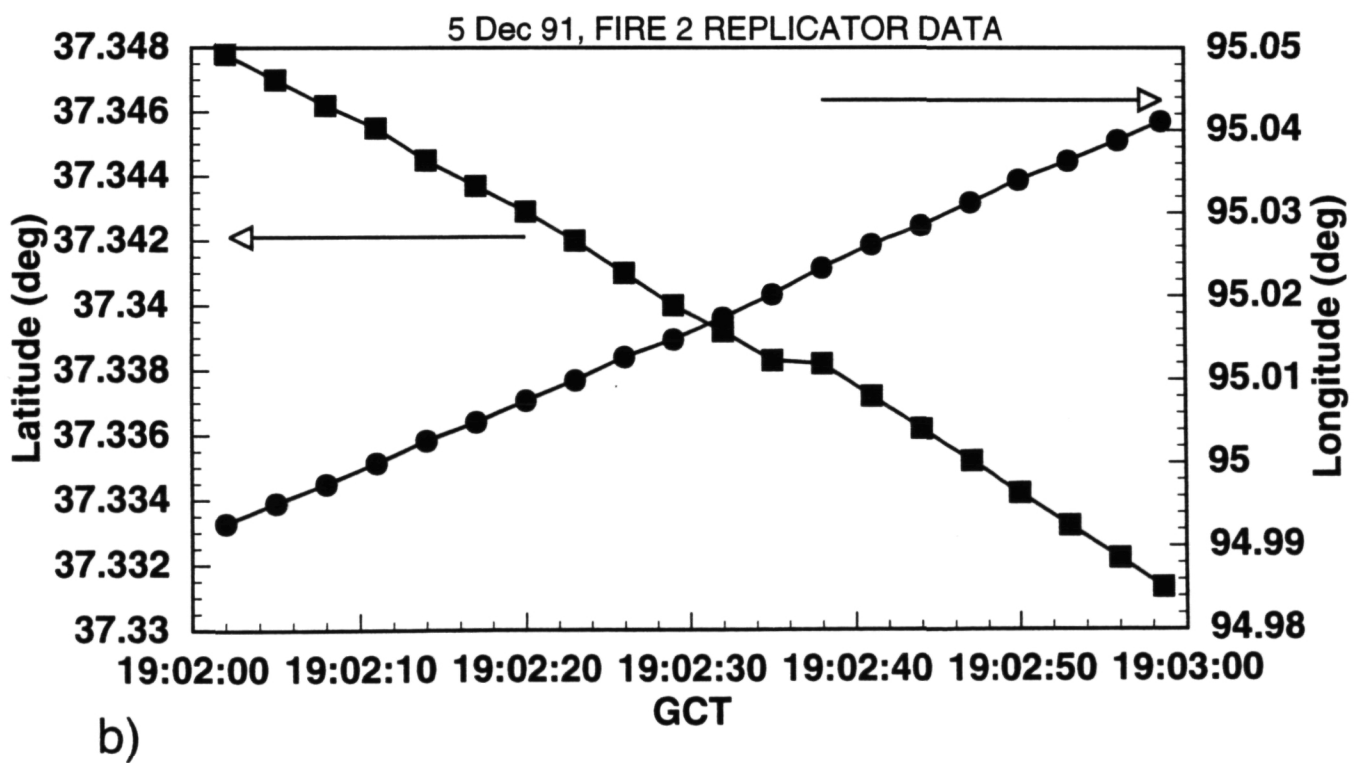
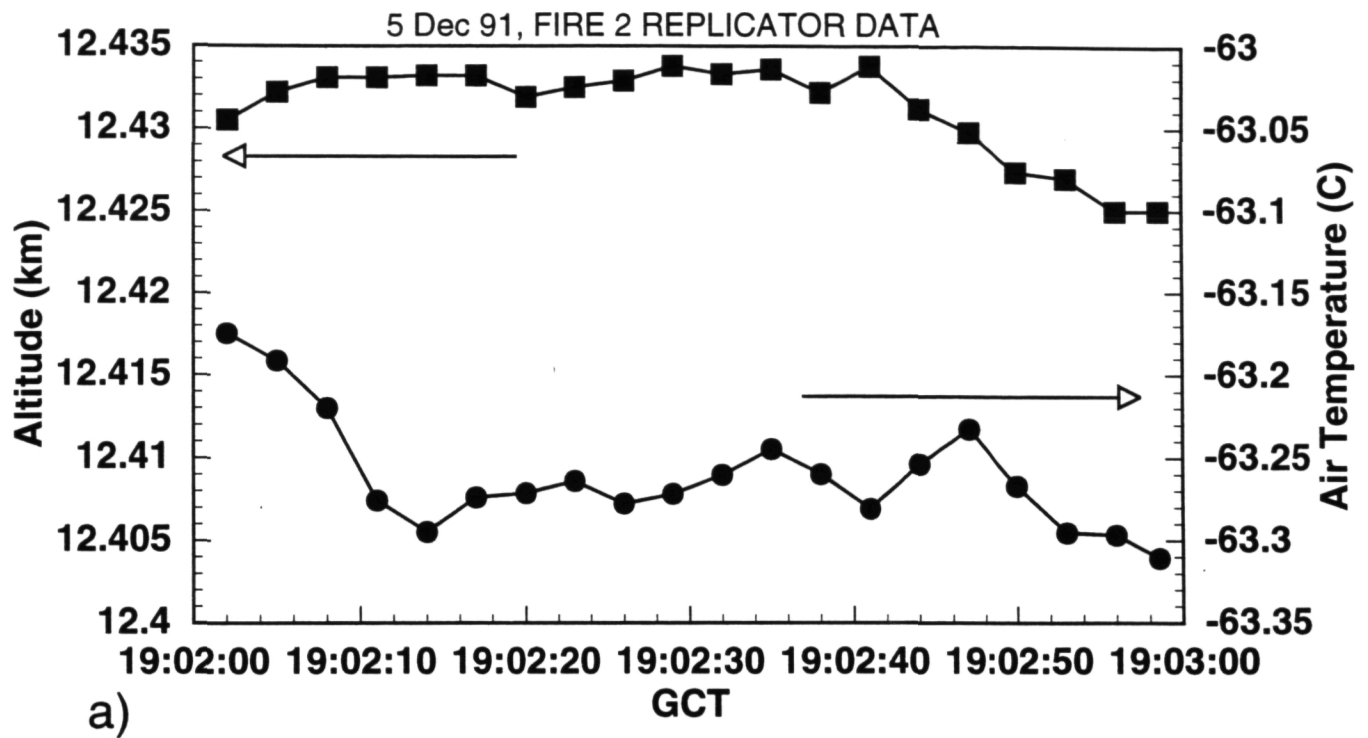
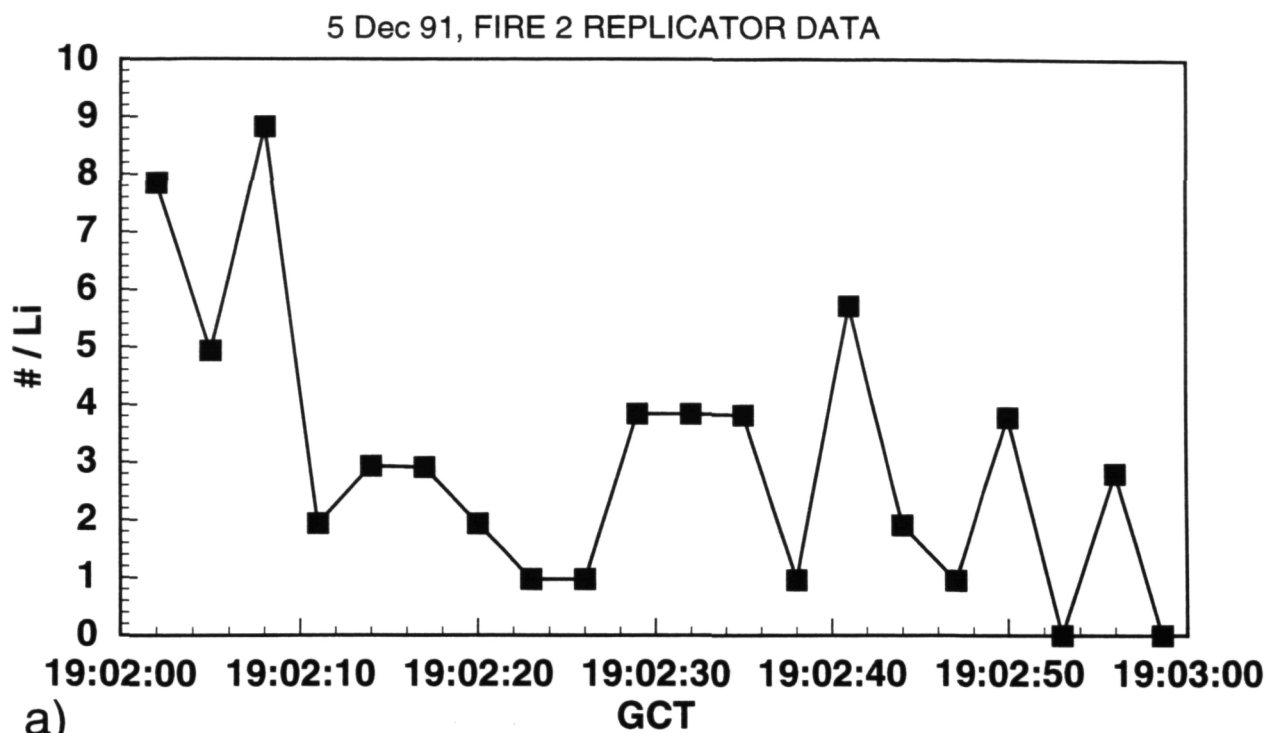
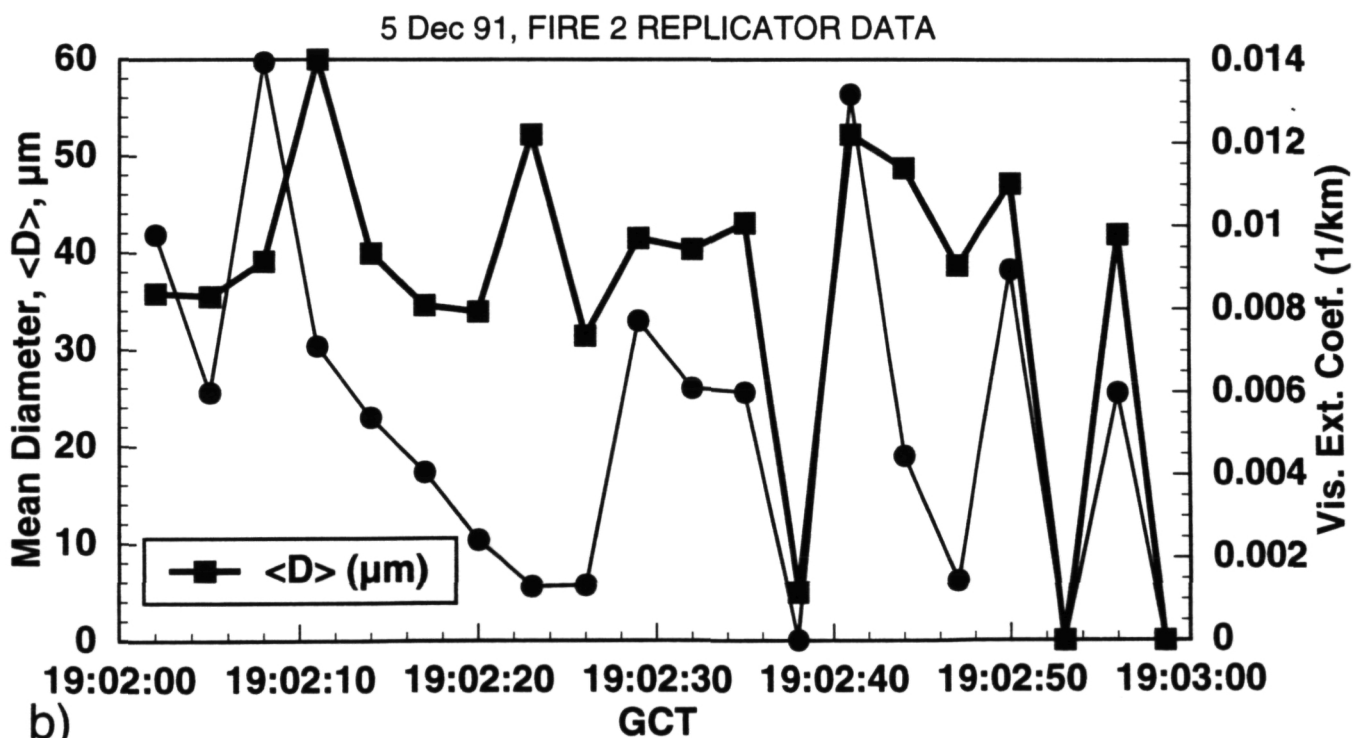


Figure 7. a) aircraft altitude and ambient air temperature, and b) aircraft location.



a)



b)

Figure 8. a) Total concentration, and b) mean crystal maximum dimension and computed extinction coefficient for visible wavelengths.

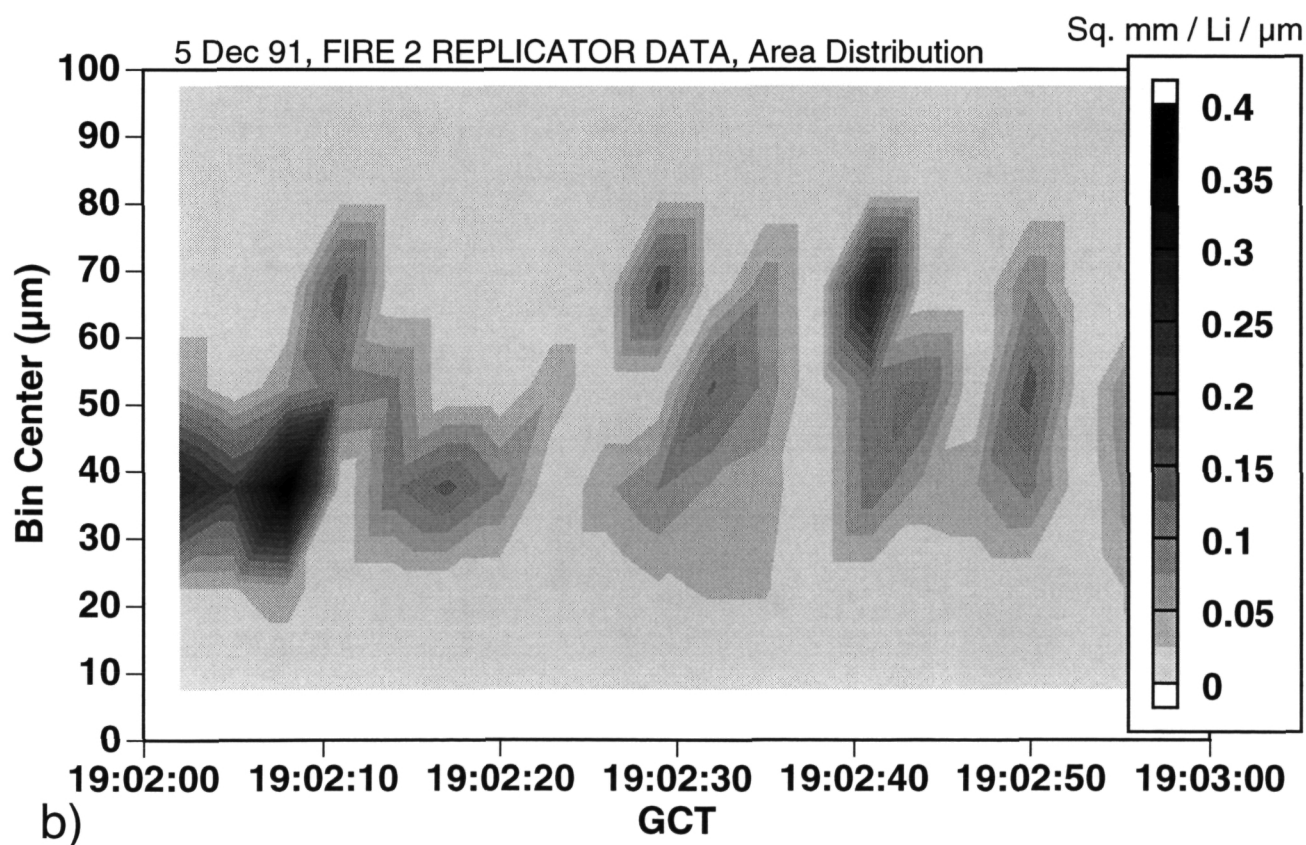
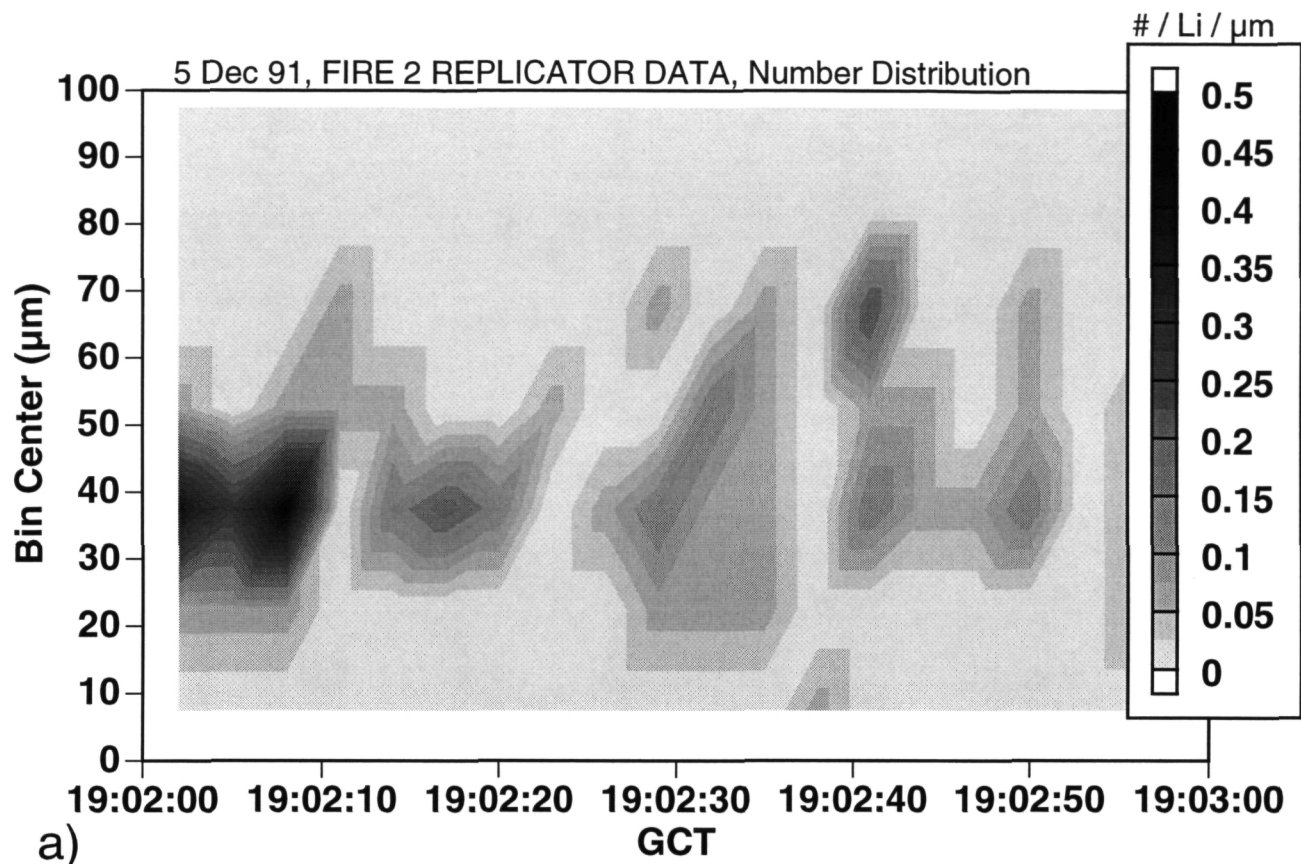


Figure 9. Time and size resolved distributions for a) number concentration, and b) area concentration.

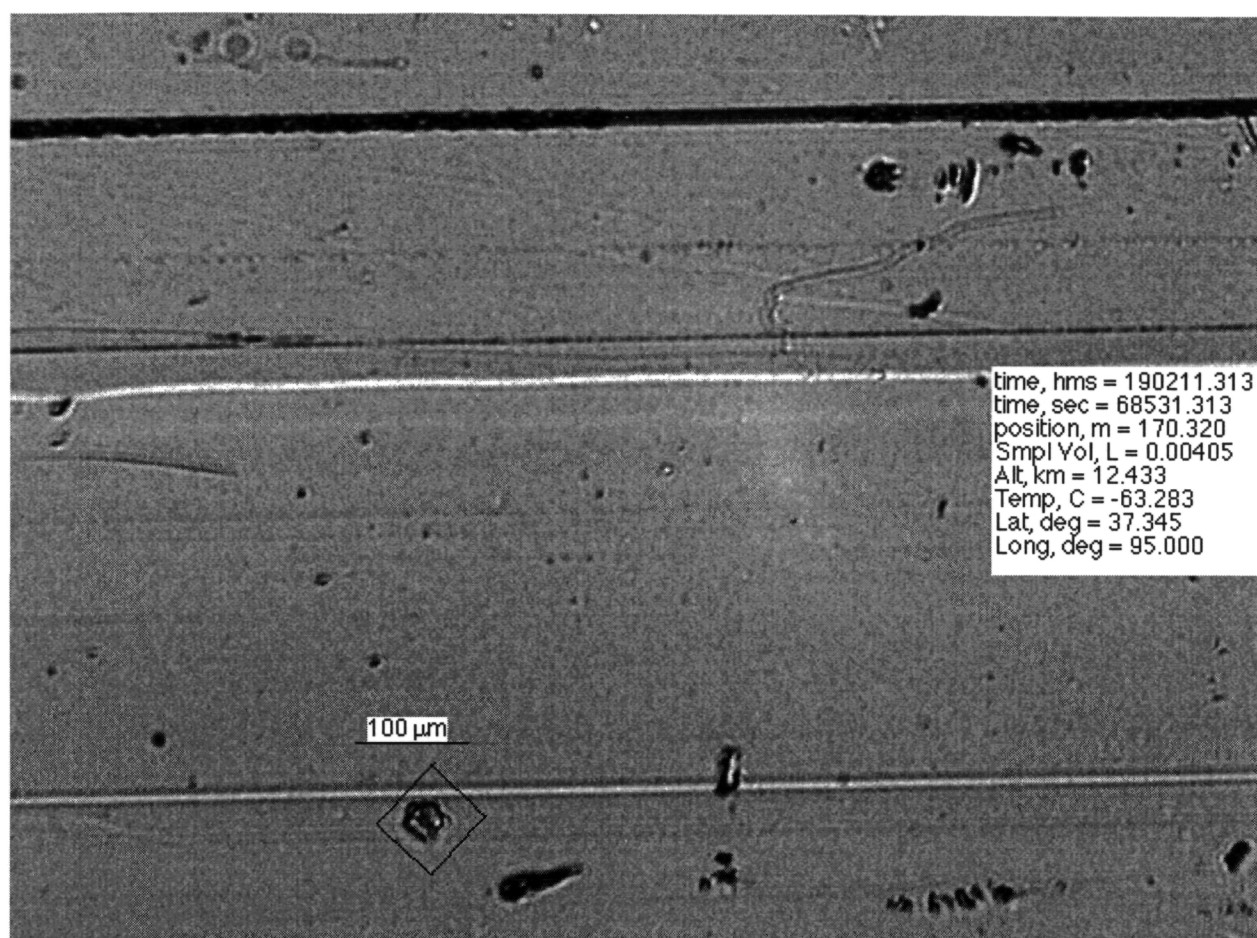


Figure 10. Crystal from 5 Dec 91, FIRE 2.

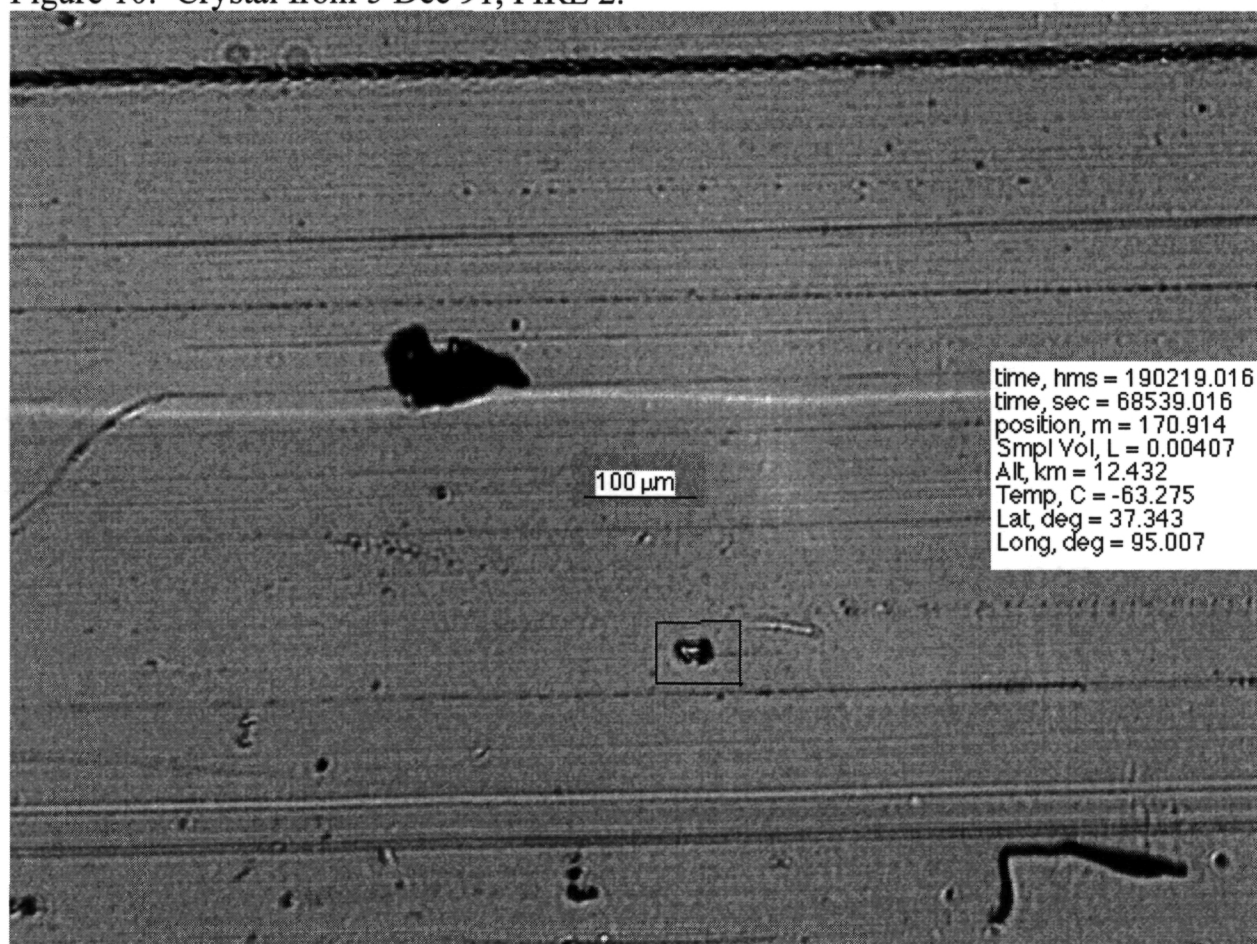


Figure 11. Crystal from 5 Dec 91, FIRE 2.

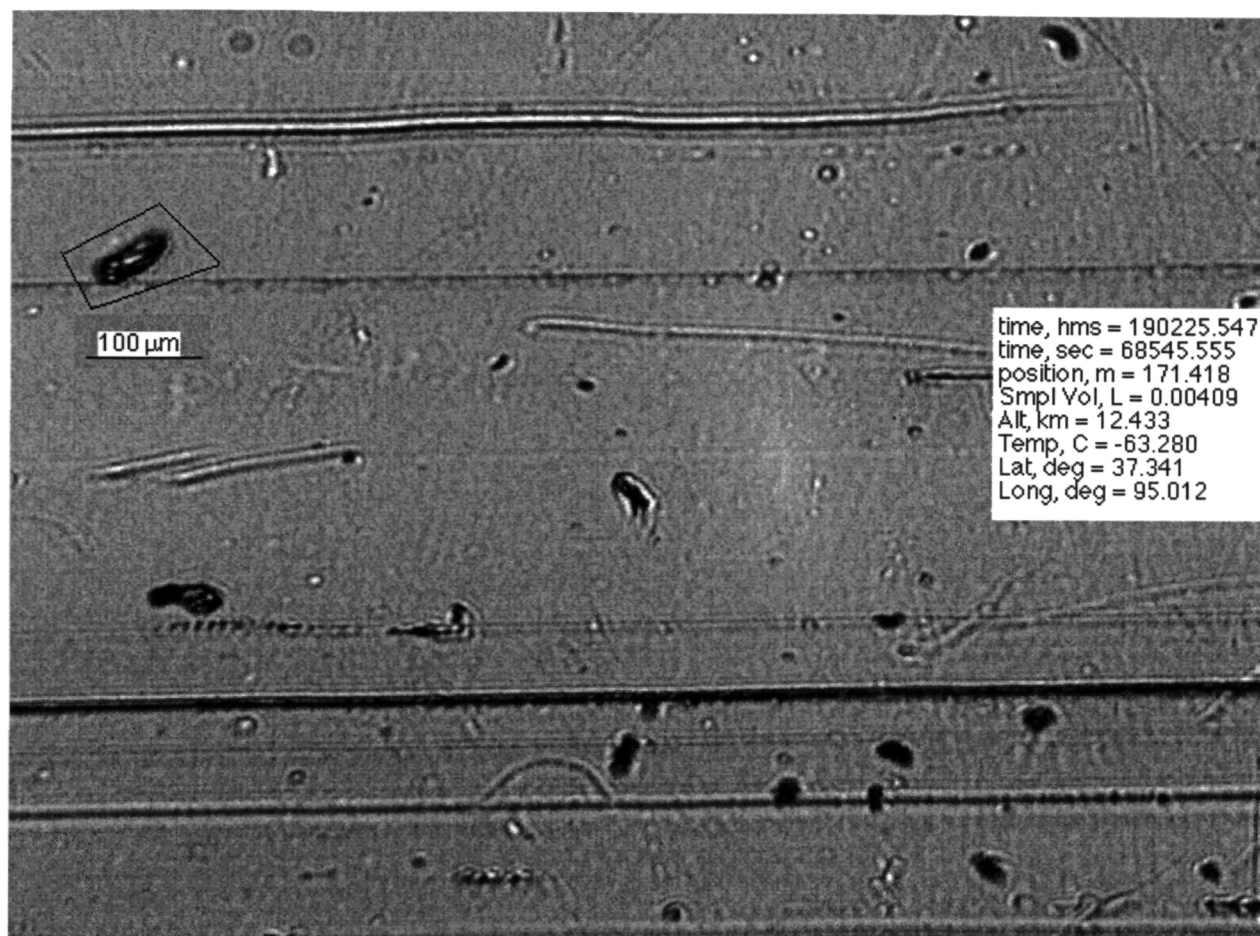


Figure 12. Crystal from 5 Dec 91, FIRE 2.



Figure 13. Crystal from 5 Dec 91, FIRE 2.

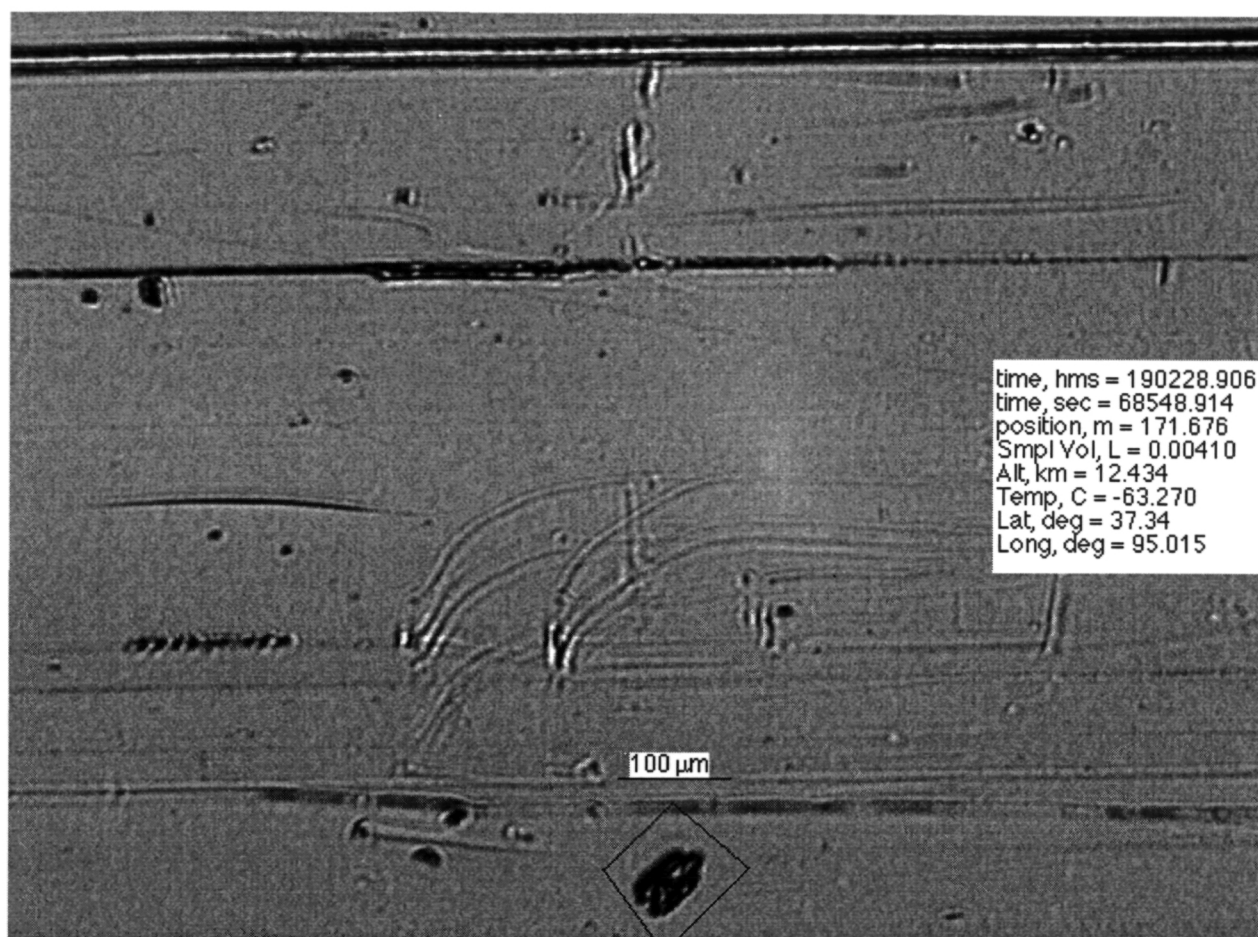


Figure 14. Crystal from 5 Dec 91, FIRE 2.

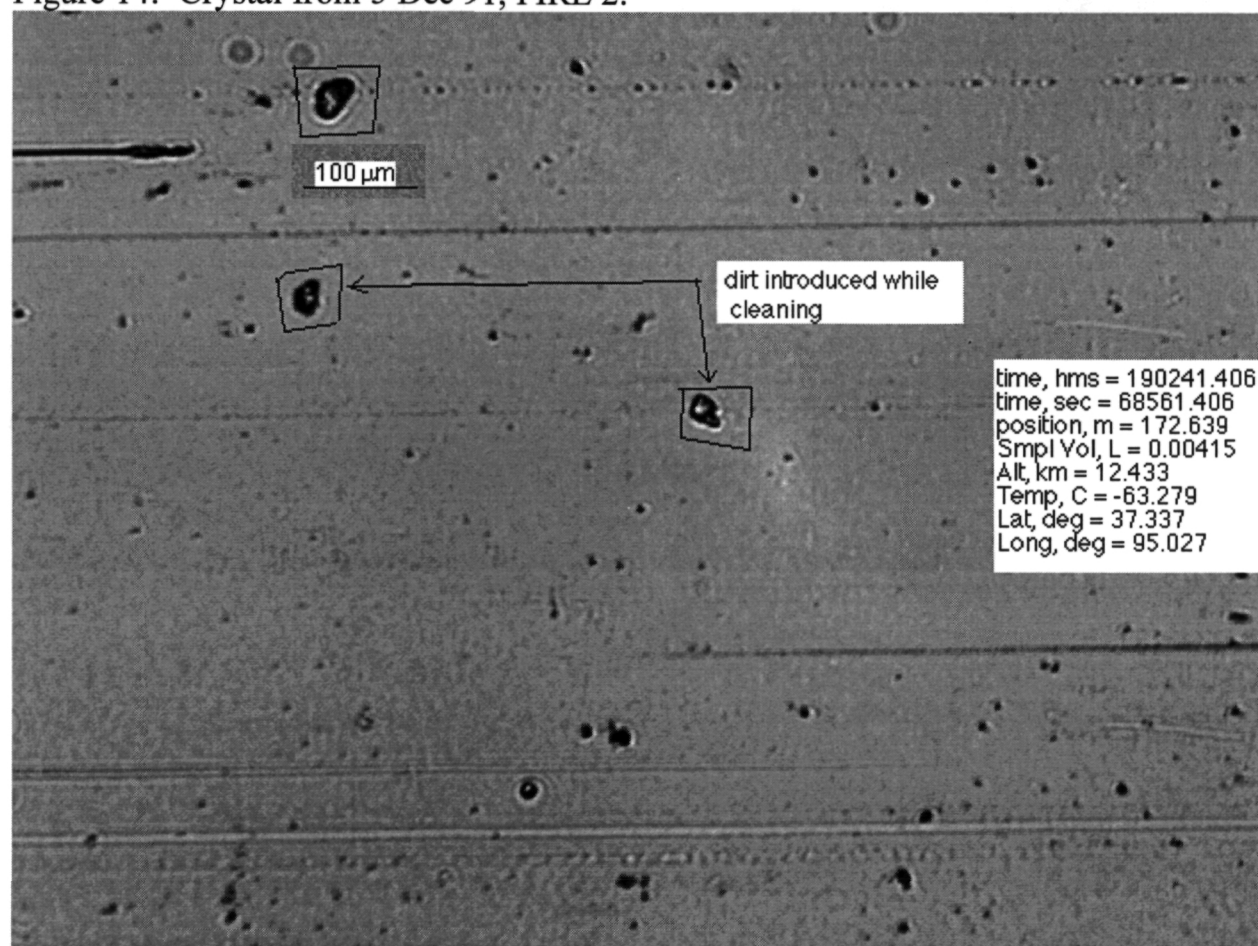


Figure 15. Crystal from 5 Dec 91, FIRE 2.

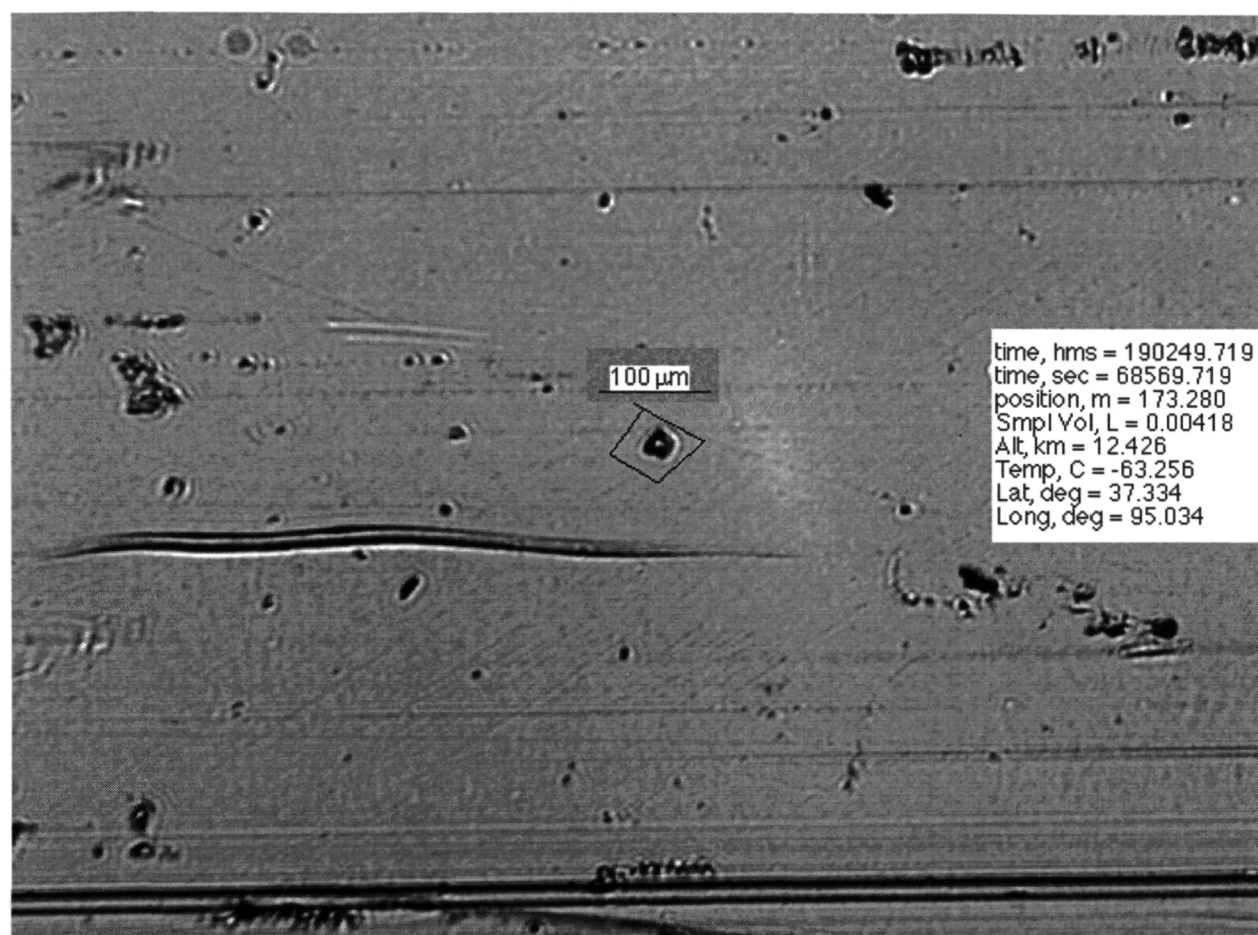


Figure 16. Crystal from 5 Dec 91, FIRE 2.

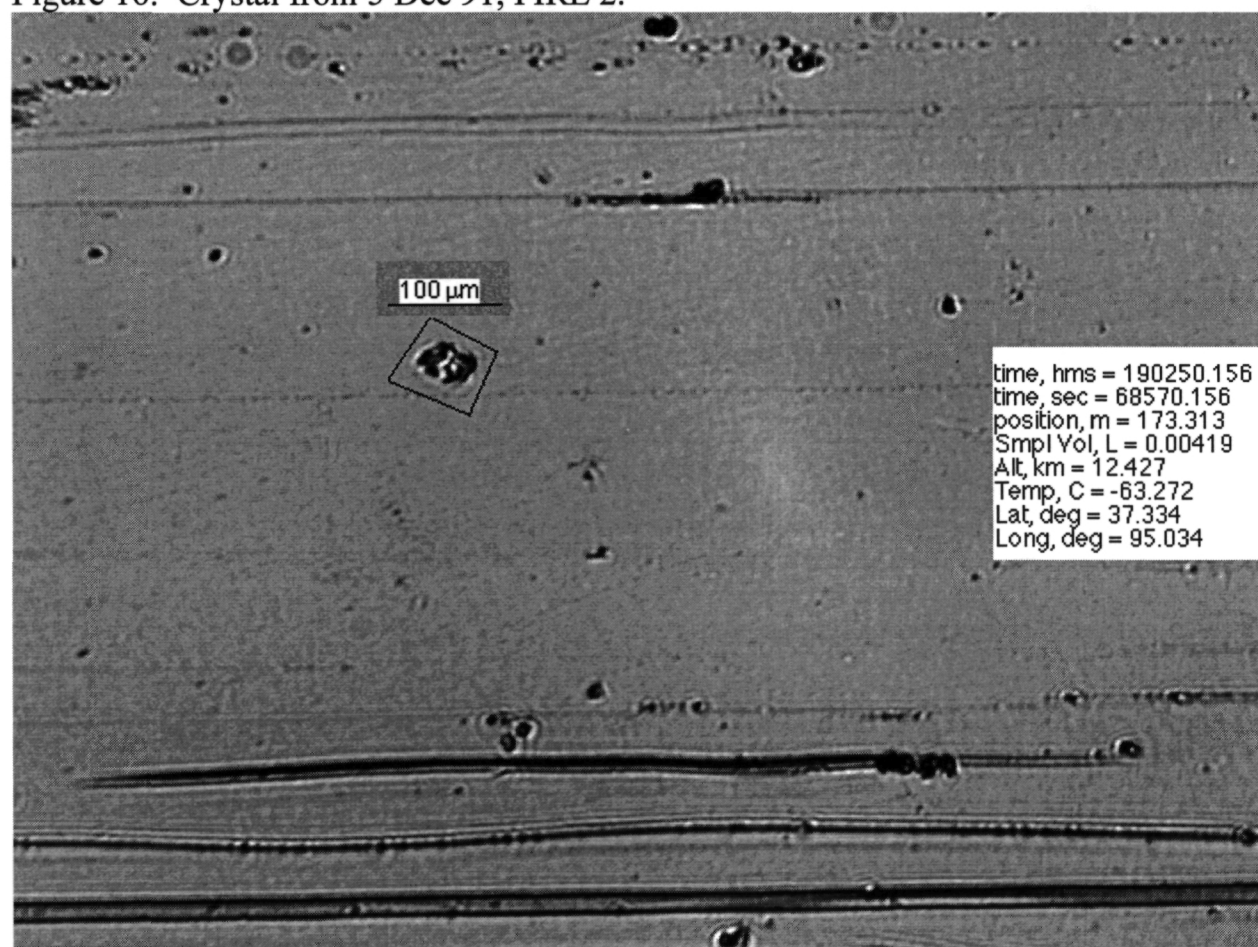


Figure 17. Crystal from 5 Dec 91, FIRE 2.